INTER-ROTATIONAL STRATEGIES FOR SUSTAINING SITE FERTILITY AND PRODUCTIVITY OF *ACACIA* AND *EUCALYPTUS* PLANTATIONS PLANTED ON STEEP SLOPES IN NORTHERN VIETNAM

By

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Submitted in fulfilment of the requirements for the

Doctor of Philosophy

UNIVERSITY OF TASMANIA

July, 2019

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Paper 1 is located in Chapter 3: Bich, N.V., Eyles, A., Mendham, D., Dong, T.L., Ratkowsky, D., Evans, K.J., Hai, V.D., Thanh, H.V., Thinh, N.V., Mohammed, C. 2018. Contribution of harvest residues to nutrient cycling in a tropical *Acacia mangium* Willd. plantation. *Forests* 9 (9): 577. doi.org/10.3390/f9090577

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Paper 2 is located in Chapter 4: Bich, N.V., Mendham, D., Evans, K.J., Dong, T.L., Hai, V.D., Thanh, H.V., Mohammed, C. 2019. Effect of residue management and fertiliser application on the productivity of a *Eucalyptus* hybrid and *Acacia mangium* planted on sloping terrain in northern Vietnam. *Southern Forests, in press*. doi.org/10.2989/20702620.2018.1555940

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Paper 3 is located in Chapter 5: this paper has been submitted to Southern Forests

Bich, N.V., Eyles, A., Mendham, D., Evans, K.J., Dong, T.L., Hai, V.D., Mohammed, C. Effect of harvest residue management on soil properties of *Eucalyptus* hybrid and *Acacia mangium* plantations planted on steep slopes of northern Vietnam. *Southern Forests, under review*.

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ABSTRACT

In Vietnam, approximately 1.3 M ha of acacia and eucalypt plantations have been established in the past three decades to supply a growing local and international demand for pulp and sawlog. Wood production over successive rotations does not appear sustainable as yields are declining and soils, especially on steep sites, are being eroded and negatively impacted. There is concern that current practices, i.e. burning harvest residues and only applying a small dose of fertilisers at planting are in part responsible for this situation and need to be changed. This thesis examines if changes in the current practices i.e. the retention of harvest residues and increased P fertilisation will improve the soil properties and productivity of *Eucalyptus* hybrid (*Eucalyptus urophylla* × *E. pellita*) and *Acacia mangium* plantations planted on steep slopes in northern Vietnam.

The first study investigated whether the decomposition of retained *A. mangium* harvest residues (branches, leaves and bark) could provide sufficient nutrients for the next rotation. The biomass and nutrient content of above-ground stand components of the previous 7-year-old *Acacia mangium* rotation were examined at harvest, and the rates of decomposition and nutrient release from the harvest residues determined. The decomposition constant k, half-life $t_{0.5}$ and release of nutrients (N, P, K, Ca and Mg) were monitored by using the litterbag technique for a 1.5-year-period. At harvesting, the total above-ground stand biomass of the previous rotation was 60.8 t ha^{-1}, comprising stemwood (42.7 t ha^{-1}), bark (8.9 t ha^{-1}), branches (6.6 t ha^{-1}) and leaves (2.5 t ha^{-1}). The retained bark on site made up one-third of the mass of all residues (harvest residues + litter + understorey vegetation) and conserved 6% Mg, 14% K, 18% P, 30% N and 41% Ca content for recycling. The decomposition rate of the leaves was the most rapid (k = 1.47 year^{-1}; $t_{0.5}$ = 0.47 year), then branches (k = 0.54 year^{-1}; $t_{0.5}$ = 1.29 year) and bark (k

= 0.22 year^{-1}; $t_{0.5}$ = 3.09 year). During decomposition, the loss of nutrients from harvest residues was K ≈ Ca > N > P> Mg. Over 1.5 years of the study period, as much as 137.1 kg N ha^{-1}, 4.7 kg P ha^{-1}, 20.8 kg K ha^{-1}, 94.5 kg Ca ha^{-1} and 2.2 kg Mg ha^{-1} were recycled. The N, Ca and K, though not P and Mg released from decomposing *A. mangium* harvest residues are potentially able to meet a significant part of the demand by trees growing in the next rotation.

The second study examined whether the retention of residues, and application of phosphorus fertiliser at higher rates than the current practice, can increase rates of growth and vigour of trees, i.e. better tree form and lesser crown damage, of eucalypt and acacia plantations. A factorial combination of residue management (burning *vs*. retention) and phosphorus (P) fertiliser application at planting (15 *vs*. 100 kg ha^{-1}) treatments was applied at a steeply sloping site (slope rages from 8 – 40°). Two adjacent experiments were established, one with *A. mangium* and the other with *E.* hybrid. Standing volume (V) and leaf area index (LAI) in *A. mangium* were greater following burning; this was mostly attributable to the significantly higher survival rate of seedlings. Burning of residues was associated with increases in the number of large branches per tree, and a higher crown damage index (CDI). In the *E.* hybrid, diameter and height responses to the higher rate of fertiliser were observed at age 6 and 12 months, but not beyond. High P application also led to higher CDI. Standard fertiliser treatment, applied in amounts equivalent to 17, 15 and 8 kg ha^{-1} of N, P, K, respectively, was adequate to meet the early growth requirement of eucalypt and acacia plantations at this site.

The third study examined the effect of two contrasting harvest residue management treatments (burning *vs.* residue-retention) on soil properties i.e. soil total carbon (TC), total nitrogen (TN), extractable P (ext-P), exchangeable K (exch-K) and soil bulk density

(BD) of *E.* hybrid and *A. mangium* plantations. In this study, soil samples were collected in plots treated with similar amounts of fertiliser (applied at the current rate) but subject to contrasting residue management treatments (burning *vs.* residue-retention). The soil properties were assessed at pre-establishment, and at age one and two years following planting. The results showed that the soil properties in either *E.* hybrid or *A. mangium* plantations were not significantly different between residue retention and residue burning inter-rotational treatments. However marked variations observed in soil TC, exch-K and ext-P suggest that position on the slope masked any overall trends.

In summary, the relatively low amounts of harvest residues and high fertility levels at the site may be associated with the lack of significant growth and soil responses to the silvicultural treatments applied in this study. However, it is clear that the decomposition of harvest residues and the associated rate of nutrient release can supply a significant amount of nutrients required for stand development in the next rotation. The variation in standing volume, crown health and soil properties between slope positions suggest that factors driving any correlation of tree productivity with slope, for example surface run-off and soil erosion will need careful management to arrest potential yield decline on steeply sloping sites. Thus harvest residue retention with adequate weed and termite control may be preferential to burning on a steep slope because the residue not only can provide nutrients but reduce water run-off and soil erosion.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervisors, Prof Caroline Mohammad, Dr Chris Beadle, Dr Katherine Evans and Dr Alieta Eyles for kindly guidance, assistance, and motivation throughout my PhD studies.

I am also very much grateful to Dr Daniel Mendham, Dr Tran Lam Dong, Prof Vo Dai Hai for their useful suggestions and contributions to paper preparation. Thanks to Dr David Ratkowsky for assistance in statistical analysis. I would like to thank Mr Gath Oliver for his guidance and assistance in soil sampling, and Dr Chris Harwood, Dr Vu Dinh Huong and Dr Trieu Thai Hung for useful advice and suggestions for improving my thesis.

I would like to acknowledge with thanks the support received from Dr Nguyen Hoang Nghia, Dr Phan Minh Sang, Dr Tran Van Con, Dr Dang Thinh Trieu, Dr Tran Van Do, Dr Nguyen Toan Thang and my parents who believed in me and encouraged me to pursue the Australian Award Scholarship for studying in Australia.

I am very much grateful to Mr Le Tat Trinh and Mr Lo Van Thien for their contribution to data collection, experimental design and fieldwork. Special thanks to my colleagues in the Silviculture Research Institute of the Vietnamese Academy of Forest Sciences, Mr Hoang Van Thanh, Mr Dao Trung Duc, Mr Duong Quang Trung, Mr Le Van Quang, Miss Tran Hong Van and Mrs Hoang Thi Nhung for their assistances in fieldwork and laboratory work. Thanks to staff at Thac Ba Forest Enterprise for access to their commercial plantations for experiments as well their help in the maintenance of field experiments.

I sincerely thank all staff members and friends within the Tasmanian Institute of Agriculture (TIA), and CSIRO in Tasmania for their assistance and sharing of useful knowledge and experience.

I gratefully acknowledge financial support from DFAT (formerly AusAID) in the form of an Australian Award Scholarship (former named Australian Development Scholarship). Additional operating funding was generously provided by the Ministry of Agriculture and Rural Development (MARD) of Vietnam (implemented by the Vietnamese Academy of Forest Sciences), and by TIA.

Special thanks to my friends and family members, especially my wife – Pham Thi Luyen, my daughters – Nguyen Hong Lam (Emily) and Nguyen Thanh Mai (Melissa) for their encouragement and moral support, they greatly contributed to the accomplishment of my PhD.

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%	Percentage
ACIAR	Australian Centre for International Agricultural Research
AGB	Aboveground biomass of stand
ANOVA	Analysis of Variation
BD	Bulk density
C	Carbon
℃	Temperature (degree Celsius)
C:N (C/N)	Carbon:nitrogen ratio
Ca	Calcium
CDI	Crown damage index
CEC	Cation exchange capacity
CIFOR	Center for International Forestry Research
cm	Centimetre
cmol	Centimole
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBH; D	Diameter at breast height (1.3 m above ground level) of tree
Exch- Ca	Exchangeable calcium
Exch-K	Exchangeable potassium
Exch-Mg	Exchangeable magnesium
Ext-P	Extractable phosphorous
H	Top height of tree
K	Potassium
LAI	Leaf area index
m^2	Square metre

m^3	Cubic metre
mo	month
MAI	Mean annual increment of stand volume
MARD	Ministry of Agriculture and Rural Development of Vietnam
Mg	Magnesium
N	Nitrogen
N:P (C/P)	Nitrogen:phosphorus ratio
P	Phosphorous
pH	Soil pH
SE	Standard error
SLA	Specific leaf area
t ha^{-1}	ton per ha
TC	Total soil organic carbon
TN	Total soil nitrogen
TP	Total soil phosphorus
V	Standing volume
VAFS	Vietnamese Academy of Forest Sciences
yr	Year

CHAPTER 1

INTRODUCTION

Commercial plantations on steep slopes in Northern Vietnam (photo by Bich, N.V. 2015)

CHAPTER 1. INTRODUCTION

1.1. Problem statement

Plantation forestry is already extensive and is expanding rapidly to meet the increasing demand for wood products and to reduce pressure on harvesting natural forestry. To meet this demand, there have been many species introduced, especially exotic fast growing trees such as *Eucalyptus* and *Acacia.* According to Harwood and Nambiar (2014) the plantation forests of eucalypt and acacia species in South East Asia now exceed seven million hectares, and this area is expected to increase to meet the emerging demand of wood products in the region. However, due to limitations in land areas suitable for expanding plantations, the future of wood supply depends on maintaining and where possible increasing production per unit area from the current land base (Harwood and Nambiar 2014). There have been many attempts at sustaining and improving the productivity of plantations across successive rotations. The inter-rotation phase of a short-rotation plantation cycle includes practices such as harvesting, site management and the establishment of the next rotation. The phase plays a crucial role in the sustainability of production (Goncalves et al. 2013, Nambiar and Harwood 2014). Mismanagement during this inter-rotation phase has the potential to negatively impact future productivity, especially for short-rotation plantations (Goncalves et al. 2013, Mendham et al. 2003, Nambiar and Harwood 2014).

Harvesting short-rotation plantations may be associated with the export of large quantities of organic matter and nutrients from the site (Achat et al. 2015, Folster and Khanna 1997, Huong et al. 2015). Removing stemwood with bark from the site is a common operation practice when harvesting commercial plantations (Achat et al. 2015, Huong et al. 2015, Yamada et al. 2004). In acacia plantations, harvesting stemwood with bark of commercial size (diameter ≥ 5 cm over bark) resulted in the export of 41 – 181 t ha^{-1} of dry organic matter and 115 – 525 kg ha^{-1} of N, 14 – 56 kg ha^{-1} of P, 81 – 155 kg ha^{-1} of K, 22 – 357 kg ha^{-1} of Ca and

26 kg ha^{-1} of Mg, depending on the productivity and ages of the stand (Hardiyanto and Nambiar 2014, Huong et al. 2015, Yamada et al. 2004). In eucalypt plantations, stemwood with bark removal at harvesting led to the loss of 100 – 173 t ha^{-1} of dry organic master, and potentially exported 132 – 202, 16 – 30, 98 – 220, 172 – 1023 and 54 – 160 kg ha^{-1} of N, P, K, Ca and Mg content in aboveground stand biomass, respectively (du Toit et al. , Hernández et al. 2009, Yamada et al. 2004). In both species, bark accounted for approximately 10% of aboveground stand biomass but contained high quantities of nutrients, especially Ca (40 – 57% of total Ca content in aboveground stand biomass) (Yamada et al. 2004). Hence, debarking trees on site at harvesting would increase quantities of nutrient conservation for the next rotations.

"Slash and burn" cultivation in which the forest is clear cut, the wood removed and any remaining vegetation burnt is a traditional method of site preparation that is still used in plantation forestry in some countries, including Vietnam (Deleporte et al. 2008, du Toit 2008, Eldoma et al. 2015, Tran et al. 2011). This practice has been identified as the most adverse inter-rotational intervention (Gonçalves et al. 2004, Nambiar et al. 2015) that resulted in significant losses in growth and soil properties of eucalypts (Deleporte et al. 2008, Gonçalves et al. 2007, Mendham et al. 2003, Rocha et al. 2016a), and the tree form of acacias (Eldoma et al. 2015). These effects have been explained by the loss of almost all the organic matter (Mendham et al. 2003) and up to 86% of N and 60% of P in smoke and through volatilisation, and the loss of P, K and Ca though leaching, wind-blown ash, surface run-off and erosion (Gonçalves et al. 2007). Fast-growing short-rotation plantation acacias and eucalypts require a large nutrient supply, especially of N, P and K, at planting (Hardiyanto and Nambiar 2014, Melo et al. 2016, Mendham et al. 2017); burning therefore has the potential to reduce this supply.

In contrast, retention of harvest residues including branches, leaves and bark has been shown to lead to increased tree growth and improved soil properties in many plantations

(Gonçalves et al. 2007, Hardiyanto and Nambiar 2014, Huang et al. 2013, Huong et al. 2015, Rocha et al. 2016a). For example, the MAI of acacia and eucalypt plantations has been found to have a positive correlation with the quantities of residues maintained on the site following harvesting (Deleporte et al. 2008, Huong et al. 2015). Retention of harvest residue of a *Eucalyptus grandis* plantation in Brazil resulted in soil organic carbon (TC) and nitrogen (TN) (0 – 5 cm soil depth) that were 33% and 43% higher, respectively, seven years after establishment than when all harvest residues were removed (Gonçalves et al. 2007). Similarly, TC and TN (0 – 10 cm soil depth) increased by 17% and 11%, respectively, in a two-year-old *A. mangium* plantation in Sumatra, Indonesia when harvest residues were retained rather than removed (Hardiyanto and Nambiar 2014). This effect has been associated with a range of phenomena, including reduced export of nutrients (Achat et al. 2015, du Toit 2008, Huong et al. 2015), enhanced soil microbial activity (Achat et al. 2015, Mendham et al. 2002, Wu et al. 2011), and increased nutrient mineralization to the soils (Fernandez et al. 2009, Nzila et al. 2002b, O'Connell et al. 2004, Sankaran et al. 2008).

The decomposition of harvest residues retained on the site can provide a significant source of nutrients to the soil (Hernández et al. 2009, Shammas et al. 2003, Versini et al. 2014). In a *Eucalyptus globulus* plantation in western Australia, harvest residues potentially contributed as much as 176 kg ha^{-1} of N, 15 kg ha^{-1} of P and 276 kg ha^{-1} of K to soil fertility during the first year following harvest (Shammas et al. 2003), and in a *Eucalyptus dunnii* plantation in Uruguay 176, 20, 375, 460 and 92 kg ha^{-1} of N, P, K, Ca and Mg, respectively, during the first 2 years following harvest (Hernández et al. 2009). This suggests that retention of harvest residues can conserve nutrients for recycling, hence may potentially reduce the costs for fertiliser application in the next rotation.

On steep slopes, soils are particularly vulnerable to erosion associated with heavy rainfall and surface runoff (Sidle et al. 2006). When harvest residues are retained, decomposing residues can act as a buffer against nutrient losses by immobilisation of some nutrients, especially N and Ca (Hernández et al. 2009, Shammas et al. 2003) that can reduce leaching during the early stages of plantation development. In addition, retention of harvest residues can prevent water run-off and soil erosion (Blanco-Canqui and Lal 2009, Costantini and Lcoh 2002, Malinda 1995). Hence retention of harvest residues may provide an option for sustaining site fertility and therefore productivity of eucalypt and acacia plantations on steeply sloping sites.

Considering the high amounts of nutrients exported from the site due to harvesting (Achat et al. 2015), supplying nutrients as fertiliser are a common practice in short-rotation commercial plantation (Folster and Khanna 1997), and often improves productivity (Melo et al. 2016, Mendham et al. 2017, Xu et al. 2001). Tropical acacia plantations have been shown to respond to P applied at planting (Beadle et al. 2013, Huong et al. 2015, Mendham et al. 2017), but not K or Ca (Hardiyanto and Nambiar 2014, Huong et al. 2015); while responses of *Eucalyptus* plantations to both N and P at planting are common observation (Judd et al. 1996, Melo et al. 2016, Xu et al. 2001). However, responses can vary across sites depending on soil fertility and tree requirements (Mendham et al. 2017, Sankaran et al. 2007). As acacias are N-fixing, they are generally considered to have an increased requirement for P compared to non-leguminous species (Ingestad 1980). Responses to high rates of P at planting have also been found in eucalypt plantations (Judd et al. 1996), especially in soils with low available P (Melo et al. 2016, Xu et al. 2001). Thus, in low soil available P sites such as in northern Vietnam (Sam and Binh 2001), high rates of P applied at planting may need to be maintained for improving productivity of both acacia and eucalypt plantations.

Most of eucalypts and acacias have been planting in their non-native environment, hence the productivity of these plantations is increasingly threatened by insect pests and pathogens (Crous et al. 2017, Dell et al. 2012) which are introduced accidentally and/or have adapted to new host trees (Wingfield et al. 2015). For example, in Sumatra, Indonesia, growth rates of

Acacia mangium have been reduced by 60 – 70% due to fungal diseases (*Ganoderma* and *Ceratocystis*) (Harwood and Nambiar 2014). In both Vietnam and Malaysia, *Ceratocystis* is considered an extreme threat that caused up to 20% of tree mortality rates in some acacia plantations in Vietnam (Thu et al. 2012). Among the most serious biotic damaging agents of eucalypts in South East (SE) Asia are a gall wasp *Leptocybe invasa*, a bacterial wilt pathogen *Ralstonia solanacearum* and the fungal leaf and stem blight pathogens *Calonectria quinqueseptata* and *Cryptosporiopsis eucalypti* (Dell et al. 2012, Thu 2016). Tropical acacias and eucalypts are also affected by termites (Calderon and Constantino 2007, Ngoc et al. 2011), with up to 30% of seedlings being infested in many young acacia and eucalypt plantations across Vietnam (Ngoc et al. 2011). Thus an effective silvicultural regime for the sustainable productivity of plantations should minimise threats from pests and diseases.

In summary, in Vietnam, plantation forestry plays a crucial role in the economy of rural areas by providing wood-chip, timber or paper material (Harwood et al. 2017, Nambiar et al. 2015). In the past three decades, approximately 3.4 M ha of mainly acacia and eucalypt plantations have been established to meet growing local and international demand for pulp and sawlog product (MARD 2014, VNFOREST 2011). Most are located on sites with steep slopes, 15 – 40° (Sam and Binh 2001) and soils are dominated by acidic and leached Acrisols of low to medium fertility (Phuong et al. 2012, Sang et al. 2013). These soil has been classified as potentially sustainable for both eucalyptus and acacia plantations (Thuyet et al. 2008). With a stocking rate of 1667 – 2500 trees ha^{-1}, these plantations are generally managed on a rotation length of 5 – 8 years (Nambiar et al. 2015). Most of the resource is currently in the second and third rotation, and their productivity varies from 10 to 25 m^{3} ha^{-1} year^{-1} (Hung et al. 2016, Nambiar et al. 2015) depending on site condition as well as management inputs. Trees are harvested by clearfelling. Stemwood with bark $\geq$ 3 cm in diameter over bark is generally exported as harvested product and the remaining logging debris (including branch with diameter > 1 cm) is collected by the locals for firewood and then the cleared site is subsequently burnt (Dung et al. 2012, Huong et al. 2015, Nambiar et al. 2015). Growers of commercial acacia and eucalypt plantations often apply suboptimal amounts of organic and/or inorganic nutrients at planting (Dung et al. 2012, Nambiar et al. 2015). There is concern that soil fertility (Dong et al. 2014, Hung et al. 2017) and yields (Cao and Son 2014, Dung et al. 2012, Khiet 2014) may be declining and that current residue management practices will not be able to sustain potential yields (Dung et al. 2012, Huong et al. 2015, Nambiar et al. 2015). Scientific evidence is required to shift traditional cultivation practices and to clearly demonstrate the contribution of harvest residues to nutrient cycling and its influence on the productivity of the plantations in successive rotations on steep slopes. It is essential to understand decomposition rates and nutrient release from harvest residues in an *Acacia mangium* plantation and propose new guidelines for residue and nutrient management. It is also necessary to examine whether residue retention and higher levels of fertiliser application, especially P at planting can be used to arrest any yield decline and provide a pathway for sustaining higher yields in the longer term. Furthermore, damage from insect pests and diseases is further reducing yields (Ngoc et al. 2011, Thu et al. 2012). Since the productivity of eucalypt and acacia plantations is increasingly threated by pests and diseases, the management of pests and diseases should be considered in any silvicultural design that aims to sustainably maintain the productivity of plantations.

To deal with the above issues in the context of sustainable site management practice for short-rotation plantations of eucalypt and acacia, we need to (1) evaluate the contribution of harvest residues to nutrient cycling and effect of residue management practices on site properties and productivity of eucalypt and acacia plantations, and (2) understand the role of fertiliser addition at planting in arresting yield decline of eucalypt and acacia plantations in successive rotations. The following issues need to be addressed by this thesis:

(1) How much nutrients are exported from or retained on the site following harvesting of *A. mangium* plantations and how long does it take to decay and return these nutrients to the soil for plant uptake

(2) Does burning harvest residues at establishment lead to degraded soil and negative effect on productivity of eucalypt and acacia plantations managed on steep slopes?

(3) Are soil properties of acacia and eucalypt plantation improved by retaining harvest residues without burning?

(4) Does retention of harvest residues and application of larger amount of fertiliser compared to current practice improve productivity of eucalypt and acacia plantations managed on steep slopes?

(5) Does slope influence site fertility and productivity of eucalypt and acacia plantations?

1.2. Objectives

The main objective of this study was to examine the responses of eucalypt and acacia plantations to inter-rotational management practices in order to provide optimal options that can be used to arrest any yield decline and provide a pathway for sustaining higher yields in the longer term. The specific focus was to examine the effects of harvest residue management and fertiliser application treatments on soil fertility and productivity of *Acacia mangium* and *Eucalyptus* hybrid (*Eucalyptus urophylla* × *E. pellita*) plantations managed on steep slopes of northern Vietnam. The results would provide practical information for managing and sustaining productivity of short-rotation plantations managed on steep slopes.

To fulfil this general objective, the specific objectives of this study were:

(1) to evaluate the quantity of biomass and nutrient exported from the site due to harvesting of *A. mangium* plantations.

(2) to evaluate the quantity of residues including harvest residues and forest floor residue maintained on the site and decomposition rates and nutrient release patterns of harvest residues following harvesting of *A. mangium* plantations

(3) to compare effects of harvest residue management treatments (burning *vs.* retention) and fertiliser application (low *vs.* high levels of fertiliser) on productivity of *E.* hybrid and *A. mangium* plantations

(4) to compare the effect of harvest residue management treatments (burning *vs.* retention) on soil properties under eucalypt and acacia plantations

(5) to explore the effect of slope on soil properties and productivity of the plantations and whether the effect is attributable to the residue management treatments.

(6) to evaluate the results in relation to options for residue management and fertiliser application at planting to improve site fertility and productivity of short-rotation plantations of eucalypt and acacia managed on steep slopes.

1.3. Experimental design and data collection

Study site

The study site was located 170 km north of Hanoi at latitude 21°51'N, longitude 105°00'E, and altitude 100 m in a commercial forest area in Yen Bai province, Vietnam (Fig. 1.1A and B).

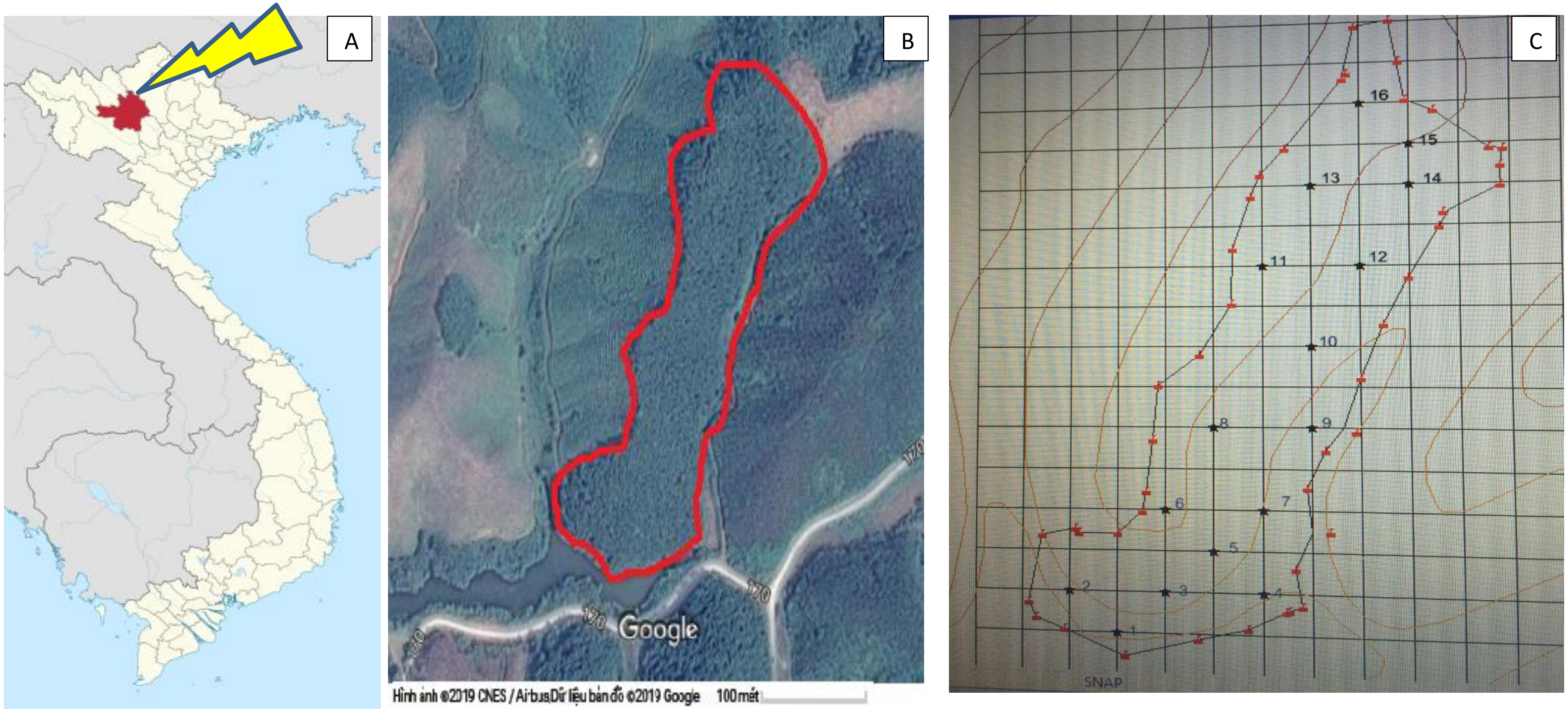

Figure 1.1. Map of the study site (A), satellite image of the *A. mangium* plantation previous harvesting (inside the red line) (B) and location of 16 representative plots (750 m^2) for measuring harvesting data of the acacia stand i.e. growth, biomass, understorey vegetation and litter (C).

Land use history

Secondary forest (degraded natural forest) on the site was converted to plantation *Styrax tonkinensis* (Pierre) Craib in the 1980s, followed by two rotations of *A. mangium* planted in 2000 and 2008. Site preparation on each occasion involved the burning of post-harvest residues and at planting, the application of small amounts of inorganic fertiliser. The previous stand of *A. mangium* was clear-felled in January 2015. The detailed measurements, analyses and descriptions of the stand were presented in Chapter 3. In brief, at harvesting the stand had a mean height of 14.5 m, stem diameter (DBH) of 13.2 cm, MAI of 13.3 m3 ha-1 yr-1 and aboveground stand biomass of 60.8 Mg ha-1.

Experimental design and layout

A randomised complete block experiment with five replications was applied to both the *A. mangium* and *E.* hybrid experiments. Four treatments were imposed: a factorial combination of forest residue management (burning *vs*. retention) and P fertiliser application (current practice *vs*. a higher level of P fertiliser). Details of the treatment combinations are given below:

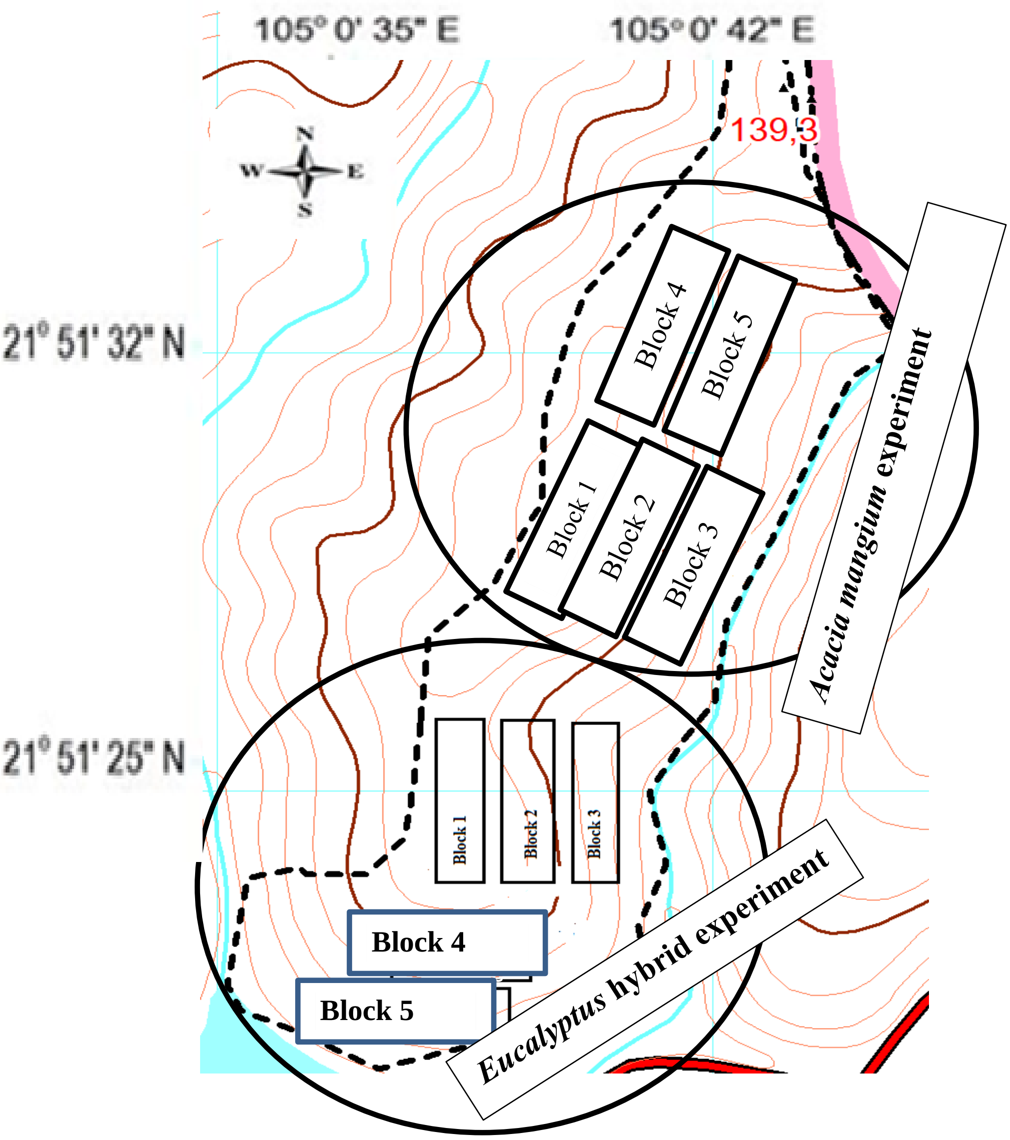

Figure 1.2. Location of blocks in the experimental site of *Eucalyptus* hybrid and *Acacia mangium* in northern Vietnam.

The two residue management treatments were

(1) S0: Residues burnt: harvest residues evenly distributed, and then all residues subsequently burnt 60 days after clear-cutting and two weeks before planting.

(2) S1: Residues retained: Harvest residues evenly distributed and no burning.

The plantation soils are dominated by acidic and leached acrisols with low available soil P (Hung et al. 2017, Phuong et al. 2012, Sam and Binh 2001, Sang et al. 2013) and P at planting is a critical requirement for growth (Hai et al. 2005, Son et al. 2006). A zero P treatment therefore was not applied and the two P fertiliser treatments were:

(1) P15: Current fertiliser practice: 17 kg ha^{-1} of N, 15 kg ha^{-1} of P and 8 kg ha^{-1} of K, applied as N:P:K 5:10:3 fertiliser.

(2) P100: High P fertilizer: As for P15 plus 85 kg ha^{-1} of P, applied as super-phosphate (16% P_2O_5), thus a total of 100 kg ha^{-1} of P.

Block	*Eucalyptus* hybrid experiment			
B1	S0P15	S1P15	S1P100	S0P100
B2	S1P15	S0P15	S0P100	S1P100
B3	S0P100	S1P15	S1P100	S0P15
B4	S1P100	S1P15	S0P15	S0P100
B5	S0P100	S0P15	S1P15	S1P100

Block	*Acacia mangium* experiment			
B1	S1P15	S1P100	S0P100	S0P15
B2	S0P100	S1P100	S1P15	S0P15
B3	S0P100	S1P15	S0P15	S1P100
B4	S0P100	S0P15	S1P100	S1P15
B5	S1P100	S0P100	S1P15	S0P15

Notes: S0: Burning residue treatment S1: Residue retention treatment

Figure 1.3. Randomised complete block experimental design with 5 replications applied to examine the effect of residue management treatments and fertiliser application treatments in *E.* hybrid and *Acacia mangium* in Yen Bai, Northern Vietnam.

Total treatment area for the 40 plots (20 plots of 20 × 30 m for *Eucalyptus* hybrid, and 20 plots of 25 × 30 m for *A. mangium*) was 2.7 ha, i.e. 1.2 ha for *Eucalyptus* hybrid and 1.5 ha for *A. mangium*.

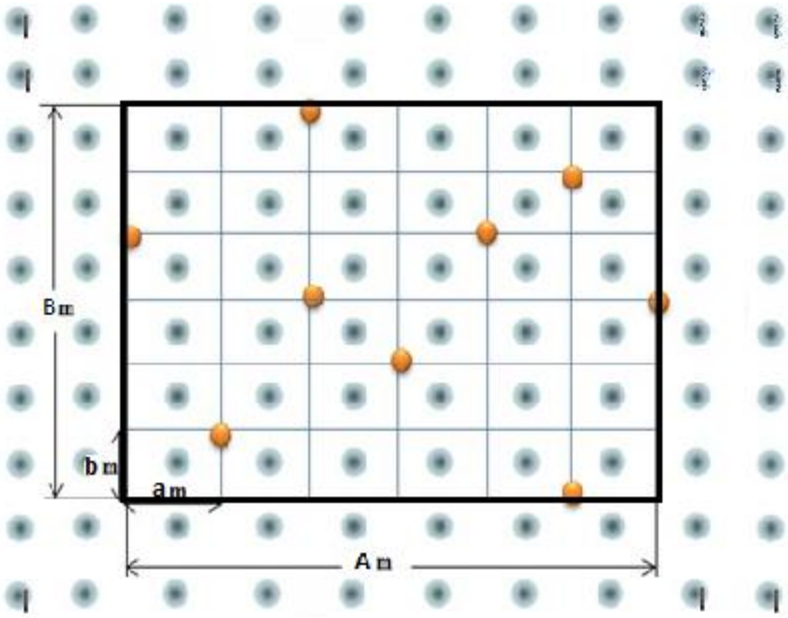

Figure 1.4. Layout of gross plot (10 trees × 10 rows), measurement plot (6 trees × 6 rows) and distribution of soil sampling points in plot. The distances A = 18 m, a = 3 m for both species; while B = 12 m and 15 m, b = 2 m and 2.5 m in *E.* hybrid and *A. mangium* experiment, respectively.

The seedlings were sourced from a national seed orchard in Ba Vi established by the Forest Tree Improvement and Biotechnology Research Institute, Vietnamese Academy of Forest Sciences, Hanoi. Seedlings were planted in 30 × 30 × 30 cm planting holes with spacing between plants of 2 m × 3 m (1666 trees ha^{-1}) in the *Eucalyptus* hybrid trial, and 2.5 m × 3 m (1333 trees ha^{-1}) in the *A. mangium* trial. To minimise loss of P due to high P-fixing capacity of the Acrisols soil (Sam and Binh 2001), fertiliser was applied in the base of the planting hole without mixing through the soil and covered by a soil layer before planting the trees. Weed control was applied to whole area across all treatments, using a wood-handle machete, at six monthly intervals following planting and until canopy closure. The tree measurements were made on net plots (a sampling area within the treatment area) of six rows of six trees to provide plot areas of 216 m^2 and 270 m^2 in *Eucalyptus* hybrid and *A. mangium*, respectively. Each net plot was surrounded by two rows of buffer trees on all sides.

Data collection and distribution between Chapters:

In the previous stand (rotation): Before harvesting of the 7 years old *A. mangium* plantation, growth and biomass of the plantation were measured in 16 representative plots (Fig. 1.1C). Litter and understorey vegetation were also measured. Plant samples were collected for fresh/dry mass conversion and nutrient concentration analysis. Details of previous stand data collection have been presented in Chapter 3.

Experiment 1: Decompostion and nutrient release from decomposing harvest residues

The detail of experimental design and data collection have been presented in Chapter 3.

All the data collect in previous stand and in Experimental 1 were used for Chaper 3.

Experiment 2: Effect of harvest residue management and fertiliser application on productivity of *E.* hybrid and *A. mangium* plantations

The detail of experimental design has been presented above (also can bee seen in Chapter 4). Data collection has been presented detail in Chapter 4. The data collected in Experiment 2 (except soil data) was used for Chapter 4.

Sub-experiment 2: Effect of harvest residue management on soil properties in *E.* hybrid and *A. mangium* plantations.

This experiment used soil data collected in 10 plots which treated as P15 fertilsier but two contrast residue management (burning vs. retention). The detail of experimental design and data collection has been presented in Chapter 5.

All soil data collected in sub-experiment 2 was used for Chapter 5.

1.4. Thesis outline

This thesis consists of six chapters including an introduction, a literature review, three experimental chapters and a general discussion. The three experimental chapters are written in paper format as they have been, or are intended to be, submitted for publication. The outline of these chapters is as follow:

Chapter 1. Introduction that gives context to the three experimental chapters and the research questions addressed

Chapter 2. Literature review which critically examines the available information in relation to inter-rotational management in acacia and eucalypt plantations in Vietnam and the impact of this management on sustainable production

Chapter 3. Contribution of harvest residues to nutrient cycling in a tropical *Acacia mangium* Willd. plantation. The chapter clarified the first and second objectives which evaluated the amounts of biomass and nutrient exported from or retained on the site following harvesting of a seven-year old *A. mangium* plantation as well as the decomposition rates and nutrient release pattern of harvest residues over an eighteen-month study period.

Chapter 4. Effect of residue management and fertiliser application on the productivity of a *Eucalyptus* hybrid and *Acacia mangium* planted on sloping terrain in northern Vietnam. This chapter dealt with the third and a part of the fifth objective which examined the effect of harvest residue management treatments and fertiliser application at planting on tree parameters that potentially influence the productivity such as tree growth, leaf area index, tree form and crown vigour as well as the influence of slope and its position on the productivity.

Chapter 5. Effect of harvest residue management on soil properties of *Eucalyptus* hybrid and *Acacia mangium* plantations planted on steep slopes in northern Vietnam. This chapter dealt with the fourth and a part of the fifth objective which compared soil properties between harvest residue management treatments as well as between slope/slope position in eucalypt and acacia plantations.

Chapter 6. General discussion and conclusion which considers the significance of the results and their potential impact on inter-rotational management practices. Recommendations for future research are given.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2. LITERATURE REVIEW

2.1. Plantation forestry in SE Asia and Vietnam

Global planted forests have been expanding rapidly to supply the growing demands of the wood industry and environmental services such as biodiversity, carbon sequestration and watershed protection (Kanninen 2010). During the period between 1990 – 2015, there were 60.4 million ha of new plantations established worldwide (FAO 2015). By 2015, the total area of plantation forest globally was 277.9 million ha; 56% in the temperate zone, 15% boreal, 20% tropical, and 9% subtropical (FAO 2015). Approximately 18 – 19% of these areas have been planted with exotic fast-growing species (Payn et al. 2015). In 2012, about 46.3% of world's industrial roundwood was sourced from plantation forests (Payn et al. 2015). Just over one third of this product is currently harvested from intensively managed forest plantations and this proportion is predicted to increase to nearly 44% by 2020 (FAO 2010).

Most plantations in the tropics are managed as short-rotation monocultures based on 5-to-10 year growth cycles although there are some plantations of teak in Java and India, and hybrid pine in Queensland, Australia that are managed over longer rotation cycles typically of >25 years (Harwood and Nambiar 2014). Short-rotation plantations with fast-growing species represent a relatively new venture in forest management (Vance et al. 2014).

In SE Asia, the area under planted hardwoods was estimated to be 25.6 million ha in 2010, accounting for 8.7% of the total forest area in SE Asia (FAO 2010). *Acacia* and *Eucalyptus* have been reported as the main species used for plantations in this region with at least 2.6 million ha of acacias and 4.3 million ha of eucalypts established during the past two decades (Harwood and Nambiar 2014). Managed on 5-to-8-year rotations, these plantations have been used for a range of purposes including land rehabilitation, paper pulp, firewood and tannin production (He et al. 2011, Nambiar et al. 2015). While pulp wood is the dominant product, there has been increasing production of small logs for a range of solid and engineered wood products (Nambiar and Harwood 2014).

In Vietnam, plantation forests have been extensively extended since the 1990s following the launching of Government Programs such as "greening the barren lands and denuded hills" (327 Program) and "5 million hectare reforestation program" (5MHRP) (Tuan et al. 2004). In 2010, the Vietnamese Government announced policies to support the development of the forestry sector for the period between 2011 and 2020 (MARD 2010). These policies aim to protect the 13.4 Mha of existing natural forest and plantations as well as increase the forest cover to 45% of total land area by 2020. By 2013, approximately 3.4 Mha of mainly acacia and eucalypt plantations had been established (MARD 2014). The quantity of timber harvested from plantations is currently 2–3 M m^3 yr^{-1} (MARD 2015) which has made a crucial contribution to the economy of rural areas by providing export wood-chip or timber for Vietnam's growing furniture industry (Hai et al. 2009a, Nambiar et al. 2015). However, due to limitations in suitable land areas for plantation expansion, the future of wood supply depends on maintaining and where possible increasing production per unit area from the current plantation land base (Harwood and Nambiar 2014).

In addition, large areas of commercial plantations are planted on steep slopes and managed by variety of public and private agencies including small growers (Nambiar et al., 2015). Despite increased silvicultural knowledge applied elsewhere in Vietnam, the current practices in commercial plantations on steep slopes generally involve burning post-harvest materials for site preparation (Nambiar et al., 2015; Hung et al., 2017) and applying only small amounts of organic/inorganic fertiliser at planting (Dung et al., 2012; Nambiar et al., 2015). There has been limit studies compared the productivity of plantations across rotations in Vietnam (Huong et al, 2015; Harwood and Nambiar 2014). Huong et al., (2015) reported increasing in productivity of *Acacia auriculiformis* across rotations, but this results may not be representative for current practices as the site had been applying advanced site management techniques (retention of harvest residues and applying fertiliser at planting, etc.) as well as genetic improvement applied in the following rotations. Nevertheless, there have been growing concern about decline in productivity of plantations in the following rotations due to poor management practices (Dung et al., 2012, Dong et al., 2014) as well as increasing in threats from pests and diseases (Thu et al., 2012). Thus, new approaches are required to sustain productivity over successive rotations.

2.2. The management of harvest residues and its effect on soil properties and productivity of hardwood plantations

In hardwood plantation ecosystems, harvest residues (plant materials including non-commercial logs, branches, leaves and bark) deposited on the site following logging of plantations, plays an important role in determining nutrient budgets for the plantation system (Achat et al. 2015, Hernández et al. 2009, O'Connell 1997, Shammas et al. 2003). Large amounts of harvest residues are commonly deposited on the sites (Achat et al. 2015, Gonçalves et al. 2007, Hardiyanto and Nambiar 2014) and are a significant source of nutrients (Achat et al. 2015, Huong et al. 2015, Shammas et al. 2003) that can be recycled to the soil (de Souza et al. 2016, Hernández et al. 2009, Shammas et al. 2003). Thus, understanding the dynamics of nutrient release under different harvest residue treatments underpins the development of best practice residue management required for sustaining site fertility and productivity.

2.2.1. Potential loss of biomass and nutrients associated with harvest residues

Clear-cutting at the end of rotations is a common practice (Achat et al. 2015, Nambiar et al. 2015), especially in short-rotation plantations i.e. eucalypts and acacias. After clear cutting, tree components are generally divided into those for commercial production (stemwood) and those for non-commercial production called harvest residues i.e. stem bark, top-end stems, branches, leaves, stumps and roots. Theoretically, only stem wood is used for commercial purposes and should be taken from sites (Achat et al. 2015, Huong et al. 2015, Nambiar and Harwood 2014). However, in reality, the total amounts of biomass and nutrients removed from a site after harvesting vary, depending on the species and harvesting regimes i.e. stand age and harvesting intensity (Achat et al. 2015, Gonçalves et al. 2008, Nambiar and Harwood 2014).

In a meta-analysis of more than 100 studies, Achat et al. (2015) showed that nutrient exports from a site increased when the number of tree components harvested increased. For example, removing stem wood with its bark + branches increased nutrient exports from the sites from 26% to 31% compared to the removal of only stem wood with bark. Whole tree harvest (stem wood with bark + branch + leaf) increased the amount of nutrient exports by 40% to 68% compared to removal of only stem wood with bark. Nutrient exports even under whole tree harvesting are significantly decreased (by 28 – 38%) if harvesting is carried out in winter or after a delay period which allows the foliage to dry and fall off the branches (Achat et al. 2015). These results indicate that harvest residues represent a rich source of nutrients that can be potentially removed from the site following logging of the plantations (Achat et al. 2015, Gonçalves et al. 2008, Miller

1984) depending on the intensity of the regime. In Vietnam most species used for commercial plantations are fast growing species managed in short rotation of 5 to 7 years (Dong et al. 2014, Hardiyanto and Nambiar 2014, Kien et al. 2014, Nambiar et al. 2015), and a high harvest intensity is applied (Dung et al. 2012, Huong et al. 2015).

Foliage generally accounts for a small percentage of total tree biomass (less than 5%) but nutrient content in foliage is generally high (from 15 – 20%) (Achat et al. 2015, Deleporte et al. 2008, Huong et al. 2015). Similar to foliage, stem bark also contains significant proportions of nutrients (Achat et al. 2015, Hai et al. 2009a, Hardiyanto and Nambiar 2014, Huong et al. 2015). For example, in *Eucalyptus globulus*, bark accounted for only 10% of the aboveground biomass but contained 50% of the calcium in harvest residues (Mendham et al., 2003). In acacia plantations, bark accounted for 7 - 10% of the total aboveground biomass but 36-39% of the calcium (Hardiyanto and Nambiar 2014, Huong et al. 2015, Nambiar and Harwood 2014). Thus if high harvesting intensity cannot be avoided, maintaining foliage and bark or delaying the firewood collection until leaves and other debris has fallen off is the good way to minimise nutrient exports from a site (Achat et al. 2015, Huong et al. 2015, Nambiar and Harwood 2014). This knowledge is crucial to helping a forest grower minimise the losses of nutrient due to harvesting.

Harvesting age also influences the amount of nutrient exported following logging (Achat et al. 2015, Miller 1995, Nambiar and Harwood 2014). The contribution to total tree biomass of foliage and thin branches (tree components with high nutrient concentrations) is larger in young stands than in old stands (Achat et al. 2015, Hai et al. 2009b). For instance, branch and leaf biomass of *Eucalyptus urophylla* was 12.83% and 24.25% of total biomass, respectively, at age 1 year but decreased to 6.95% and 4.19% at age 7 years (Hai et al. 2009b).

The effect of species on nutrient export can also be influenced by the quality or actual nutrient content of their harvest residues (Hardiyanto and Nambiar 2014, Huong et al. 2015, Mendham et al. 2008). In *Acacia mangium* in Indonesia (Hardiyanto and Nambiar 2014, Siregar et al.), *Eucalyptus globulus* in western Australia (Mendham et al. 2008, Shammas et al. 2003), and in *Eucalyptus urophylla* in China (Xu et al. 2008) with all species harvested intensively, the most significant nutrient loss was of nitrogen, followed by Ca or K and P. At the end of the first rotation of *A. auriculiformis* in Vietnam, the removal of whole trees, litter and understorey led to the loss of 284.8 kg ha^{-1} N, 157.8 kg ha^{-1} K, 46.9 kg ha^{-1} Ca and 42.9 kg ha^{-1} P (Huong et al. 2015).

Plantation productivity is another factor that influences the amount of biomass and hence potential nutrient export at harvest (Hardiyanto and Nambiar 2014, Huong et al. 2015, Nambiar and Harwood 2014). In an *A. auriculiformis* plantation across rotations in Vietnam, increasing productivity from 10.6 to 28.3 $m^3ha^{-1}yr^{-1}$ between the first and the second rotations doubled the amounts of biomass and nutrients exported from the site when the same harvesting regime was applied (Huong et al. 2015).

2.2.2. Decomposition rates and nutrient release from harvest residues

The decomposition of plant residues plays an important role in nutrient cycling as well as balancing and maintaining ecosystem function (Ge et al. 2013, Krishna and Mohan 2017). Plant residues are decomposed through the action of various decomposers such as fungi and bacteria that obtain their nutrients from dead plant materials (Krishna and Mohan 2017). Decomposers break down cells of dead plants into simpler substances which can become available for plant uptake. Slow decomposition rates can lead to the building up of organic matter and nutrient stocks in soil; while fast decay rates can provide significant amounts of nutrients recycling to the soil surface (Isaac and Nair 2005, Krishna and Mohan 2017, Olson 1963). Decomposing harvest residues can be a significant source of nutrients (Hernández et al. 2009, Shammas et al. 2003, Versini et al. 2014). For example, Shammas et al. (2003) determined that the harvest residue decomposition of a 7-year *E. globulus* plantation in western Australia could potentially contribute 176 kg ha^{-1} of N, 15 kg ha^{-1} of P and 276 kg ha^{1} of K to soil fertility during the first year following logging. Similarly, Hernández et al. (2009) estimated that the decomposing harvest residues of a 9-year old *E. dunnii* plantation released 176, 20, 375, 460 and 92 kg ha^{-1} of N, P, K, Ca and Mg, respectively, 2 years following harvesting in Uruguay.

2.2.2.1. Methods for studying residue decomposition

Various techniques have been used for assessing residue decomposition and the release of nutrients i.e. mass balance, litterbag, tethered leaves and cohort layered screen (Krishna and Mohan 2017). Among these methods, litterbags are extensively used for studying the decomposition of harvest residues at the soil surface (Bachega et al. 2016, Bärlocher 2005, Hernández et al. 2009, Krishna and Mohan 2017, O'Connell 1997, Shammas et al. 2003). Based on this method, fresh leaf litter is placed in litterbags, which are then inserted into the litter layer of the soil and then collected periodically to quantify the quantities of mass remaining. The problems associated with the litterbag technique is the selection of mesh size; too small a mesh may limit the entry of soil organisms but a larger mesh may cause particle loss (Krishna and Mohan 2017). In order to minimize these drawbacks, O'Connell (1997) suggested that a 2-mm mesh was necessary to limit the leakage of small fragments but allow access by decomposer organisms.

2.2.2.2. Factors influencing residue decomposition

The decomposition rates of harvest residues is influenced by a range of abiotic and biotic factors (Aber and Melillo 1982, Ge et al. 2013, Krishna and Mohan 2017, Powers et al. 2009, Puttaso et al. 2011, Sohng et al. 2014). The physico-chemical environment, the substrate quality of the residue and the decomposer community present have been listed as the three major factors controlling the decomposition process of residues (Couteaux et al. 1995, Ge et al. 2013, Melillo et al. 1982, Puttaso et al. 2011, Tian et al. 2007).

Environmental factors:

Temperature is considered as a prime factor in determining decomposition rates (Hobbie 1992, Krishna and Mohan 2017, Meentemeyer 1978). It has been shown that litter decomposition is sensitive to temperature (Kirschbaum 2000, Lloyd and Taylor 1994) and, within a certain range, soil microbial activity rises exponentially with soil temperature (Kirschbaum 1995).

Effect of residue substrate quality:

Residue substrate quality depends upon the plant species and type of plant material (leaf, stem, root and bark). The substrate quality of plant residue is measured through its chemical composition i.e. nitrogen, phosphorus, potassium and major cell wall components (lignin, cellulose and hemicelluloses) (Ge et al. 2013, Krishna and Mohan 2017, Ngoran et al. 2006, O'Connell 1997).

It has been clearly shown that residue decay patterns are dictated by its quality i.e. the initial concentration of N or the C/N ratio, concentration of P or C/P ratio, and lignin concentration or the lignin to nutrient ratio (Ge et al. 2013, Hernández et al. 2009, Ngoran et al. 2006, O'Connell 1997). In general, species or components with a high concentration of N, low C/N ratios and low lignin content have higher decay rates (Ge et al. 2013, Krishna and Mohan 2017, Powers et al. 2009). In tropical regions lignin/P ratio and C/P ratio are good parameters for predicting decomposition rates, because the supply of P is limited in comparison with N (Cornwell et al. 2008, Ge et al. 2013, Powers et al. 2009).

Residue quality in terms of ease of decomposition, typically reduces during the decomposition process as a result of a) the loss of easily attainable carbon and b) the accumulation of recalcitrant compounds (Gaudinski et al. 2000, O'Connell 1997). Early litter decomposition rate is generally fast because it is influenced by nutrient content, water-soluble carbon compounds and the structure of carbon compounds, but at later stages, litter decomposition rate is dominated by the lignin and cellulose/lignin ratio (Couteaux et al. 1995).

Effect of decomposer community:

The soil fauna and microbial populations present at various stages of decomposition influence the residue breakdown rate (Bini et al. 2013, Dilly et al. 2001, Gatiboni et al. 2011). Soil fauna play an active role in the cycling of nutrients (Wu et al. 2011) and influence the rate of nutrient recycling through diverse ways; microbial grazing, faecal deposition, the mixing of litter with the mineral soil as well as spreading microbial inoculum (Gatiboni et al. 2011).

Among the soil microbes, fungi are the lead decomposers of organic matter in comparison to other microorganisms (Kjoller and Struwe 1992, cited in (Krishna and Mohan 2017)). Bacteria constitute 25–30% of the total soil microbial biomass and also contribute significantly to litter decomposition and nutrient mineralisation (Dilly et al. 2001). Labile compounds in litter may be quickly accumulated by soil microbes resulting in a rapid decomposition rate (Gatiboni et al. 2011, Hernández et al. 2009). Compounds such as cellulose are easily cleaved by exo-enzymes into sugar sub-units, which again are readily absorbed by microbes (Krishna and Mohan 2017). However, refractory structural compounds, such as lignin and chitin, are too large to pass through cell membranes and remain unchanged due to their uneven chemical structure and complex bonding (Horner et al. 1988).

2.2.2.3. Patterns and dynamics of nutrient release during harvest residue decomposition

Previous studies showed that the patterns of nutrient release through decomposition are associated with the patterns of decomposition (mass loss) and dynamics of nutrient concentrations during decomposition (Hernández et al. 2009, Shammas et al. 2003).

Patterns of residue decomposition are commonly assessed through estimating decomposition rates represented by a decay constant (k) and the half-life of decomposition ($t_{0.5}$) (Olson 1963, Palviainen et al. 2004, Xu and Hirata 2005). High values of k or low values of t_{05} signifies high rates of decomposition and vice versa (O'Connell 1997, Olson 1963). Hence, monitoring the amount of mass loss over time is necessary for estimating the decay constant and half-life of decomposition. Decomposition rates are influenced by a multitude of interactions between the quality of the harvest materials, soil nutrients and climate conditions (see section 2.3.2) which all contribute to influencing decomposer populations and activities (Ge et al. 2013, Krishna and Mohan 2017, Powers et al. 2009, Tian et al. 2007).

Leaf is the most rapidly decomposed component (Hernández et al. 2009, O'Connell 1997, Shammas et al. 2003) compared to branches and bark, reflecting the faster rates of decomposition and higher amounts of nutrient concentration in leaves compared to branches and bark (de Souza et al. 2016, Fahey et al. 1991, Hernández et al. 2009, Rocha et al. 2016b, Shammas et al. 2003). Decomposition rates of bark, branch and non-commercial logs components are slower depending on the species and/or environment (Hernández et al. 2009, O'Connell 1997, Shammas et al. 2003). In a *Eucalyptus globulus* plantation in western Australia, the decomposition constant (k) and half-life decay ($t_{0.5}$) of leaf components were 1.54 year^{-1} and 0.45 years, respectively, while k and t_{05} estimated for bark were 0.22 years and 3.1 year^{-1} and for branches (0.5 – 2 cm) was 0.21 years and 3.5 year^{-1} (Shammas et al. 2003). In comparison, decomposition rates in a Uruguayan *E. dunnii* plantation under a more temperate climate were slower compared to western Australia, with k estimated for leaf, litter, branch, non-commercial logs and bark being 0.81, 0.33, 0.19, 0.18 and 0.12, respectively (Hernández et al. 2009).

Potassium appears to be the most rapidly released element from all harvest residue components (Hernández et al. 2009, Rocha et al. 2016b, Shammas et al. 2003) predominantly due to direct leaching after logging (Hernández et al. 2009, Shammas et al. 2003). In comparison, the release of other elements i.e. N, P, Ca, Mg is slower and their release is more variable among harvest residue components and across regions (Krishna and Mohan 2017, Nzila et al. 2002b, Palviainen et al. 2004, Powers et al. 2009, Shammas et al. 2003). In mixed boreal forest, 40% of the initial P content was released 3 years after clear-cutting, but there was no net release of N which was attributed to the significant N accumulation in root and branch harvest components in relation to N released by foliage (Palviainen et al. 2004). In temperate eucalypt plantations, release of P in harvest residues was comparable to the pattern of the dry matter loss, while Ca and

N were significantly accumulated, up to approximately 175% of Ca and 70% of N above their initial content (Hernández et al. 2009, Shammas et al. 2003).

Compared to eucalypts, much less is known about nutrient release from the decomposition of acacia harvest residues, particularly of bark residue (Hardiyanto et al. , Hernández et al. 2009, Laclau et al. 2010). In Vietnam, trees are commonly harvested with their bark in commercial plantations. Thus it is important to clarify the impact of bark removal on nutrient export. While bark of acacia trees represent only 9 – 10% of the total aboveground stand biomass, at harvesting, it can contribute 35 – 47% of N, 12 – 15 % of P, 25 – 34% of K and 49 – 61% of the Ca content (Hardiyanto and Nambiar 2014, Huong et al. 2015). Debarking the trees on site at harvesting can substantially reduce the export of nutrients (Hardiyanto and Nambiar 2014, Huong et al. 2015), its retention may potentially reduce the costs of fertiliser application in the next rotation.

2.2.3. Nutrients exported at harvesting and soil nutrient pools

Quantifying the nutrients exported from a site due to harvest residue removal or inputted to a site if harvest residues are retained and understanding the relationship of nutrient contents in harvest residues with nutrients stocked in the soil is very important (Achat et al. 2015). It influences the decision about which nutrients need to be compensated for in successive rotations to maintain the productivity of plantations (Foster and Bhatti 2006).

Nitrogen and P potentially exported due to harvesting are reported as low compared to total N and P stocks in the soil profile (1 m soil depth) under all types of harvest (N and P outputs are <10% and <2% of total soil N and soil P, respectively) (Achat et al. 2015, Deleporte et al. 2008). However, the potential exports of other nutrients were found to be high compared with their available levels in soil stocks, particularly when whole tree harvest was carried out (Achat et al. 2015, Deleporte et al. 2008). Research in eucalypt plantations in the Congo showed that C, K, Ca, Mg and N contents in harvest residues and litter under a stem wood removal regime, in comparison to the soil pool (1 m depth) prior to harvest, amounted to 31% of organic C, 25% of K, 32% of Ca and 112% of Mg but only 9% of N (Deleporte et al. 2008).

It is essential for forest growers to understand the contribution of harvest residues to nutrient cycling as well as soil fertility before deciding which fertiliser regime should be applied. In a region where repeated intensive harvesting is applied, addition of fertiliser to compensate for nutrient losses will be needed to avoid the reduced productivity over successive rotations e.g. there were no growth responses of *Acacia auriculiformis* in South Vietnam to P fertiliser in the second rotation, but a strong response to P fertiliser in the third rotation (Huong et al. 2015).

2.2.4. Effects of burning harvest residues on nutrient loss

In “slash and burn” cultivation the forest is clear cut, wood is removed and any remaining vegetation burned. This is a traditional method of site preparation still used in plantation forestry in some countries, including Vietnam (Sam 1994, Tran et al. 2011). Partial or complete burning following short-rotation timber harvesting may increase nutrient availability at the soil surface (Deleporte et al. 2008, Gonçalves et al. 2007, Nambiar and Harwood 2014). This observed increases in nutrient availability, probably due to the ‘ash-bed effect’ following burning (Chambers and Attiwill 1994, Giardina et al. 2000, Knoepp et al. 2004) may however, be short lived (Atwell et al. 1999), depending on the nutrient and site condition. Nevertheless, burning residues can reduce the ecosystem nutrient pool level, negatively influence long-term soil fertility (Gonçalves et al. 2007) and leads to increasing site degradation (Boyer and Miller 1994, Nambiar and Harwood 2014, Yang et al. 2003). Gonçalves et al. (2007) in *Eucalyptus grandis* plantations in Brazil, assessed that the complete burning of harvest residues and litter after harvesting, resulted in the direct losses of 86%, 60%, 49%, 11%, 29% and 84% of N, P, K, Ca, Mg and S, respectively, of the content contained in aboveground biomass.

Nutrient losses from a site due to burning residue are augmented by the volatilisation of nutrients during burning from the soil organic matter in topsoil and the wind removal of ash from the site (Giardina et al. 2000, Gonçalves et al. 2007, Kumaraswamy et al. 2014b). N and C fractions are highly volatile (Trabaud 1994). Carbon and nitrogen are easily vaporised, followed by C, Na, Ca, P, K and Mg (Raison et al. 1985b, Trabaud 1994). C-losses may be more than 97% of the combustible material. Nitrogen begins volatilising at a relatively low temperate of about 200℃ (Boyer and Miller 1994) and its volatilisation increases to about 60% at 700 ℃ (Evans and Allen 1971, Knight 1966). Nutrient losses are therefore very strongly dependent on burning intensity (temperature) and fuel load. For example, nitrogen losses after prescribed burning in the southern Appalachian forests were 20 kg ha^{-1} under low-intensity burns, increasing to more than 400 kg ha^{-1} under high-intensity burns at sites with heavy fuel loads (Vose and Swank 1993). Nitrogen losses are higher in eucalypt plantations whatever the intensity; N losses were estimated to be between 125 and 500 kg ha^{-1} under low and high fire intensities, respectively (Nambiar and Kallio 2008).

In comparison to C and N, losses of P, Ca, Mg and Na are lower (Trabaud 1994) and associated with both particulate and non-particulate mechanisms (Raison et al. 1985b). Small amounts of Ca and Mg are volatilised at 800-900 ˚C (Evans and Allen 1971, Raison et al. 1985b), K is volatised when the temperature is above 550℃ (Trabaud 1994). Up to 90% of P contained in combustible fuel has been reported as transferring to the atmosphere (Gonçalves et al. 2007, Raison et al. 1985b). However the degree of transfer depends on factors such as temperature, the forms of P in the fuel, the cation content of the ash and the amount of ash transported (Raison et al. 1985b).

When a high intensity burn is applied after clear fell harvesting on a steep site, the potential for nutrient losses is even greater as a consequence of both volatilisation and increased runoff, leaching and erosion associated with steep slopes (Costantini and Lcoh 2002, Gonçalves et al. 2007, Sidle et al. 2006).

2.2.5. Effects of residue management on soil properties

2.2.5.1. Effects of residue management on soil chemical properties

<u>Soil organic carbon (TC) and nitrogen (TN):</u>

Soil organic carbon (TC) is an important indicator of soil productivity (FAO 2017). The influence of TC on productivity is through impact on physical properties such as aggregation, water holding capacity and hydraulic conductivity (Tiarks and Ranger 2008), but TC is also an important nutrient store. In the network project run by the Centre for International Forestry (CIFOR), conducted in eight countries and at sixteen experimental sites the TC of the surface soil (0-10 cm soil depth) varied considerably over a range of biophysical environments and forest management conditions, from 5.4 to 66.5 g kg^{-1} with a mean value of 29.4 g kg^{-1} (Tiarks and Ranger 2008). Monoculture systems and clear cutting can result in significant losses of soil TC (Folster and Khanna 1997, Macedo et al.

2008) depending on the management regime. A long-term study (16 years) across two rotations of *E. grandis* in Brazil, Rocha et al. (2016a) found that the removal of harvest residues was associated with a decrease in topsoil (0-5 cm) TC until year 11 in the study. There may be an initial increase in soil TC after burning (Gonçalves et al. 2007) but this decreases with time (Rocha et al. 2016a) and burning is most often associated with reduced soil TC (Mendham et al. 2003, Rocha et al. 2016a). Harvest residue management has a more positive influence on soil TC in hardwood plantations (Gonçalves et al. 2007, Hardiyanto and Nambiar 2014, Huang et al. 2013, Huong et al. 2015, Mendham et al. 2003, Rocha et al. 2016a), although its impact will vary widely between species, sites and stand age (Huong et al. 2015, Kumaraswamy et al. 2014b, Mendham et al. 2008, Tiarks and Ranger 2008). For example, at the South African eucalypt site in the CIFOR network project, retention of harvest residues after harvesting increased TC by 9 g kg^{-1} (from 66 to 75 g kg^{-1}) 2 years after establishment, but little additional change was found between 2 and 7 years (du Toit et al. 2008). By contrast, harvest residue retention had no effect on soil TC under *A. auriculiformis* in South Vietnam and *E. urophylla* in Guangdong, China during the first two years although soil TC did subsequently increase (Huong et al. 2015, Huong et al. 2008, Xu et al. 2008).

Soil TN has been found to decrease with increased harvest intensity (Achat et al. 2015, Huong et al. 2015, Huong et al. 2008, Nambiar and Harwood 2014). For example, removing all harvest residues and litter following the harvesting of a 7-year-old *A. auriculiformis* in Vietnam resulted in declining TN one year after planting while TN remained steady in residue-retained treatments (Huong et al. 2015, Huong et al. 2008).

Tiarks and Ranger (2008) summarising the outcomes of the CIFOR network project stated that the effect of inter-rotational interventions such as clear cutting, harvest residue management and replanting on soil TC and soil TN were not significant enough to impact the future productivity of the plantations. However, the productivity at many of the 16 sites increased significantly in following rotations when both the harvest residues was retained and additional fertiliser applied (Hardiyanto and Wicaksono 2008, Huong et al. 2015, Mendham et al. 2008) and there may have been an additive effect of harvest residue retention and fertiliser application. The effect of harvest residue retention does indeed vary with site fertility (Mendham et al. 2008, Sankaran et al. 2007). At low productivity sites, the positive effect of harvest residue retention on soil N can last for years, while at high productivity sites, this effect disappears quickly or is not observed (Mendham et al. 2008).

<u>Soil phosphorus:</u>

There are many different methods of measuring extractable P and data referring to soil P is not always strictly comparable. Available soil P is reported to vary significantly across sites in tropical forest plantations (Dong et al. 2014, Hung et al. 2016, Huong et al. 2015), from 0.8 to 62.6 mg kg^{-1} (average of 6.4 mg kg^{-1}) (Tiarks and Ranger 2008).

The effect of residue management on soil P is dependent on the inherent properties of the soil and the quantities of harvest residues remaining on the site (Huong et al. 2015, Mendham et al. 2003, Tiarks and Ranger 2008). For example, at a site in Guangdong China, available P in topsoil (0-10 cm) increased from 0.7 mg kg^{-1} with harvest residue removal to 1.5 mg kg^{-1} with retention of residues from a whole tree harvest (double harvest residues) (Tiarks and Ranger 2008). In *A. mangium* planted in South Vietnam harvest residue retention (double slash) was found to result in small but consistent increases in extractable soil P compared to harvest residue removal treatment (Huong et al. 2015). In contrast, soil available P was not influenced by harvest residue retention in *E. globulus* in western Australia (Mendham et al. 2003), probably due to the low proportion of P from harvest residues compared to that available in soil pools.

In tropical plantations soil available P appears to be more significantly reduced under acacia than eucalypts (Tiarks and Ranger 2008). Soil extractable P was assessed at 5 acacia and 5 eucalypt sites in the CIFOR network trials. Soil extractable P decreased for all five acacia sites but only at one of the five sites under eucalypts (Tiarks and Ranger 2008). The largest reductions in soil extractable P (from 3.4 to 1 mg kg^{-1}) were found at 3 sites under *A. mangium* in Riau, Indonesia five years following establishment (Siregar et al.). Similar results were also observed in *A. auriculiformis* in Vietnam (Huong et al. 2015) and *A. mangium* in Indonesia (Hardiyanto and Nambiar 2014) with P declining by up to 35% compared to the initial levels. This reduction in soil P under acacia needs careful consideration for successive rotations. In a second acacia rotation in the Congo the problem of N-limitation was overshadowed by increased P-limitation (Koutika et al. 2016). P deficiency in third rotation *A. auriculiformis* meant a significant response in tree growth to P fertiliser even with inter-rotational residue retention (Huong et al. 2015). While soil P reduction is not always as marked it can still happen in tropical hardwood plantations; extractable soil P decreased after 7 years from 6.0 mg kg^{-1} to 4.0 mg kg^{-1} under *E. grandis* in Brazil (Gonçalves et al. 2007). Management of P under short-rotation acacia and eucalypt plantations is critical for maintaining site fertility and the productivity of successive rotations.

Soil pH:

Soil pH is generally used as an indicator of soil base status. If soil pH is too low, some ions e.g. Al^{3+} or Mn^{2+} may reach a level that is harmful to tree growth (Nambiar and Brown 1997). The relationship between pH and soil base status is mechanistic for a specific soil, because the ion exchange relationship is controlled by soil organic matter and soil mineralogy (Tiarks and Ranger 2008). Also, in the same soil, pH may be buffered at different levels. Therefore, a better way to use pH as a meaningful index is to identify responses in pH resulting from different silvicultural treatments at the same site rather than comparing variations in pH between sites (Tiarks and Ranger 2008).

The pH (1:5 water) of surface soils (0–10 cm) under tropical acacia and eucalypt plantations has been reported as ranging from 3.6–6.0 (Tiarks and Ranger 2008). These values are in the normal range for highly weathered tropical soils (Nambiar and Brown 1997, Tiarks and Ranger 2008). Variations in soil pH at different soil depths have been found in some studies (Hardiyanto and Wicaksono 2008, Huong et al. 2008, Mendham et al. 2008). For example, the pH (1:5 water) under plantation *A. auriculiformis* at Binh Duong, Vietnam decreased from 4.8 at the surface to 4.5 at 30-50 cm depth (Huong et al. 2008). Under plantation *A. mangium* at Sodong, Indonesia pH (1:5 water) in the top soil (10 cm soil depth) was 4.08 but increased to 4.24 at 20–40 cm soil depth (Hardiyanto and Wicaksono 2008). These fluctuations are however relatively small (Nambiar and Harwood 2014, Tiarks and Ranger 2008).

Responses of soil pH to harvest residue management are observed, but pH mainly returns to the initial level prior to harvest (Gonçalves et al. 2007, Huong et al. 2008, Little et al. 2000, Mendham et al. 2008). Any responses are also small e.g. in plantation *E. grandis* in Brazil and *A. auriculiformis* in Vietnam, soil pH in harvest residue retention treatments increased by 0.1 at ages 7 and 4 (Gonçalves et al. 2007, Huong et al. 2008); retention of harvest residues and litter also increased soil pH from 4.4 to 4.6 in *E. grandis* in South Africa (du Toit et al. 2008). Responses are most often transient e.g. in *Eucalyptus* *grandis* plantation in South Africa, under residue retention treatment, soil pH was 4.2 at planting, increased by 0.9 units after 2 years, returning to 4.4 by year 7 (du Toit et al. 2008). Responses in soil pH to harvest residue retention do not persist across rotations (Huong et al. 2015, Rocha et al. 2016a). Although soil pH appears significantly increased after harvest residue burning compared to retention, these effects are also transient and do not extend beyond the first 1.5 years (Mendham et al. 2008).

The influence of species grown (acacia or eucalypt) on soil pH has been examined. Assessment methods may influence the result (Nambiar and Harwood 2014) and give rise to contrasting views. Chronosequence studies in Vietnam have indicated that acacia plantations are associated with a decrease in soil pH (Dong et al. 2014, Hung et al. 2017, Sang et al. 2013). However there was little change in soil pH under acacia and eucalypt plantations monitored for pH in the CIFOR network trial (Tiarks and Ranger 2008). The latter authors suggest that similar patterns of soil pH under acacia and eucalypt plantations mean that nitrogen-fixing acacia do not cause soil acidification, and that current management practices of acacia plantation regimes do not have a serious effect on soil chemical properties (Tiarks and Ranger 2008).

Exchangeable bases (K, Ca and Mg):

Base cations i.e. calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) are defined as the most prevalent and exchangeable cations in the soil. These ions are identified as important nutrients for plants, therefore, they play a crucial role in sustainability of plantation forest ecosystem (Nambiar and Brown 1997, Tiarks and Ranger 2008). The values of exchangeable K, Ca and Mg differ between regions and soil conditions. However, generally in acacia and eucalypt plantations in the tropics, exchangeable K in the topsoil (0 – 10 cm) is ≤ 0.5 $cmol_c$ kg^{-1}, while exchangeable Ca and

Mg ranges from 0.08 - 24.30 $cmol_c$ kg^{-1} and 0.05 – 7.13 $cmol_c$ kg^{-1}, respectively (Tiarks and Ranger 2008).

The effect of harvest residue management on total exchangeable bases has been found to vary between sites, but mostly influences the topsoil layer (0 - 10 cm) (Deleporte et al. 2008, Huong et al. 2015, Mendham et al. 2003). For example, in eucalypt plantations one year following establishment, burning or double harvest residue treatments significantly increased total exchangeable bases at 0-10 cm soil depth compared to single harvest residue removal (Deleporte et al. 2008, du Toit et al. 2008).

Harvest residue management has been found to influence specific exchangeable cations i.e. K, Ca and Mg in short-rotation plantations of acacia and eucalypt (Gonçalves et al. 2007, Hardiyanto and Nambiar 2014, Huong et al. 2015, Mendham et al. 2003). Exchangeable K, Ca and Mg significantly increased in the topsoil during the 7 years following planting of two different soil types under *E. globulus* in SW Australia with harvest residue retention when compared to harvest residue removal treatment (Mendham et al. 2003). Similarly, in topsoil under *A. auriculiformis* in South Vietnam by the end of the second rotation, exchangeable K (0.30 $cmol_c$ kg^{-1}) was significantly higher with residue retention compared to residue removal (0.26 $cmol_c$ kg^{-1}) although exchangeable Ca and Mg were not influenced by residue treatments (Huong et al. 2015). The effects on soil properties especially exchangeable ions, of burning harvest residues in acacia plantations has received little attention (Little et al. 2000). Burning has been shown to initially increase exchangeable K, Ca and Mg in eucalypt plantations (Deleporte et al. 2008, Gonçalves et al. 2007, Mendham et al. 2003), but the magnitude of changes varies between sites. In SW Australia, following the harvesting of 8-year old *E. globulus* Mendham et al. (2003) found that burning harvest residues initially increased exchangeable K, Ca and Mg of topsoil (0 – 5 cm) by 200%, 152% and 133%, respectively, compared to harvest removal treatment, but these differences were no longer significant after one year. Similarly, in plantation *E. grandis* in Brazil, exchangeable K, Ca and Mg of topsoil (0 – 5 cm) were 70%, 50% and 78%, respectively, higher with burning compared to harvest residue removal at age 10 months following establishment. The difference in exchangeable K disappeared after 10 months while exchangeable Ca and Mg remained significantly different until the end of the rotation (7 years) (Gonçalves et al. 2007).

2.2.5.2. Effects of residue management on soil physical properties

Soil physical properties play a crucial role in determining the site fertility and suitability for production forestry. The factors that support the movement and retention of water and nutrients (and their availability to plants), the penetration of roots and the flow of heat and air are all directly associated with the soil physical properties (Osman 2013). In forest soil, physical properties are generally modified by shifting cultivation, forest fires and harvesting operations (Osman 2013). This section reviews the effects of residue management on those soil physical properties that are most relevant to soil as a medium for plant growth.

<u>Effects of residue management on soil bulk density:</u>

Bulk density is an important soil property as it affects soil porosity, which in turn influences water infiltration and soil productivity (Blanco-Canqui and Lal 2009, Osman 2013, Shaver 2010). Crop residue retention can influence soil bulk density through three mechanisms (i) residue decomposition products are lighter than mineral matter, hence bulk density should decrease by dilution; (ii) residue decomposition products should promote more aggregation and thus reduce bulk density; and (iii) root activity at the surface should increase because of the improved soil water conditions resulting from residue retention and root activity in turn favours aggregation (Shaver 2010). Hence, increased quantities of crop residue may decrease soil bulk density over time (Shaver 2010).

<u>Effects of residue management on soil moisture:</u>

Water is one of the key factors that potentially limits the productivity of tropical plantations (du Toit and Dovey 2005, du Toit et al. 2008, Hung et al. 2016). Soil moisture is generally determined by soil water content (SWC), available soil water and soil water holding capacity (WHC). These parameters are governed by elements such as soil texture, soil structure, density of soil, soil temperature, and organic matter (Osman 2013). A range of phenomena e.g. soil micro-faunal activities, the densities of dead roots and the formation of organic mineral substances, affect soil vegetation and soil organic matter and hence soil capillary and porosity (He et al. 2007).

There is strong evidence that retention of harvest residues helps to reserve soil moisture in plantations (Achat et al. 2015, Adams et al. 1991, du Toit et al. 2008, Matthews 2005). In 3 years old Douglas-fir plantation in the USA, (Roberts et al. 2005) found that soil moisture in harvest residue retention treatment was significantly higher than that in removal treatment. Similarly, harvest residue retention was found to increase soil moisture in eucalypt plantations in SW Australia (O'Connell et al. 2000). This was because harvest residue improved soil water store by increasing infiltration rate, reducing evaporation and increasing soil organic matter concentration, which increases water retention capacity of the soil (Blanco-Canqui and Lal 2009).

Effects of post-harvest residue management on soil temperature:

Soil temperature influences productivity through its influence on many processes; seed germination, the absorption of water and nutrients by plants, root development, and soil microbial activity (Alexandra and José 2005). Soil surface temperatures vary widely in a forest environment and are primarily controlled by soil moisture, soil organic matter, soil cover and soil management practices (Alexandra and José 2005).

Soil surface temperatures appear to be influenced by different residue management treatments (Alexandra and José 2005, Moroni et al. 2009, Roberts et al. 2005, Yang et al. 2003). By measuring soil temperature in two contrasting residue management treatments (residue retention *vs.* residue removal) after clear cutting Moroni et al. (2009) found that soil surface temperature at 10 cm in residue removal treatment was up to 2℃ higher than that in harvest residue retention treatment. This is probably because residue can act as the buffer layer that reflects large part of solar energy back into the atmosphere to protect the soil from heating (Alexandra and José 2005). Burning of harvest residues means that soil is both heated during the burn (Alexandra and José 2005, Leonard et al. 1998, Raison et al. 1993, Yang et al. 2003) depending on the amount of residue, its spatial distribution and moisture content, wind speed and direction (Alexandra and José 2005) and exposed to the sun light that directly heats the soil (Gonçalves et al. 2007). For example, burning a large pile of eucalypt logs can cause a maximum temperature at the soil surface of 660℃ and maintaining temperature at the depth of 16.5 cm of 100℃ for 21 hours following burning (Leonard et al. 1998).

Effect of residue management on surface run-off and soil erosion:

Crop residues can act as a natural blanket that protects the soil surface against insolation and erosive impacts caused by rain and wind (Ruan et al. 2001). Residues also act as a barrier to protect the soil surface from excessive compaction, surface sealing, and crusting, reducing the breakdown and dispersion of soil aggregates (Blanco-Canqui and Lal 2009). Residues can enhance rainwater infiltration and reduce runoff and erosion (Costantini and Lcoh 2002) and residue cover is one of the most effective and cheapest ways for reducing soil erosion as it protects the soil surface (Dickey et al. 1981). In an agricultural system in Nebraska, USA, Dickey et al. (1981) found that maintaining a 20% residue cover can reduce soil erosion by 50% percent compared to a cleanly tilled field. Surface runoff is checked by the residue cover that forms a complex series of small diversion dams and slows water flow (Dickey et al. 1981). The positive effectiveness of crop residue cover however depends on the percent of soil surface covered, soil textural class, topography, intensity of rainfall, and velocity of wind (Ruan et al. 2001).

Steep slopes soils are particularly susceptible to water erosion associated with heavy rainfall and surface runoff (Bon and Harwood 2016, Khan et al. 2016, Labrière et al. 2015, Valle et al. 2014). Low yields of crops grown on hillslopes in Vietnam (Doanh and Tuan 2005) have been associated with the steepness of slopes. A research conducted in South-Western Sichuan Province, China, Khan et al. (2016) found with medium to high rainfall intensities (54−94 mm h^{-1}), mean surface runoff and sediment loss increased significantly when slope increased from 5−25°, and that loss was markedly reduced if soil was mulched (Dickey et al. 1981).

<u>Effects of residue management on soil organisms:</u>

It is known that the composition of soil organisms is strongly influenced by harvest residue management (Gatiboni et al. 2011, Wang et al. 2012, Wu et al. 2011).

Burning removes the litter and organic matter (Antunes et al. 2009, Bot and Benites 2005); it also eliminates important organisms that inhabit the soil surface and litter layer (Bot and Benites 2005) or reduces their biomass. A residue management regime that negatively impacts soil biological activity will most likely have severe long-term consequences on site productivity.

2.2.6. Effects of residue management on productivity of hardwood plantations

Tree growth and productivity responses to different residue management regimes have been shown to depend on the amounts of residues maintained on the site and the inherent soil characteristics of the site. Tree growth and productivity in plantation eucalypts and acacia residue management have been examined during a single rotation (Deleporte et al. 2008, du Toit 2008, Gonçalves et al. 2007, Hardiyanto and Wicaksono 2008, Huong et al. 2008, Mendham et al. 2008, Sankaran et al. 2007, Sankaran et al. 2008) and, in longer term studies, across rotations (Hardiyanto and Nambiar 2014, Huong et al. 2015, Rocha et al. 2016a).

Residue retention has been shown to significantly increase tree growth and productivity of both eucalypt and acacia plantations compared to residue removal (Deleporte et al. 2008, du Toit 2008, Gonçalves et al. 2007, Hardiyanto and Wicaksono 2008, Huong et al. 2008, Sankaran et al. 2007). In eucalypt plantations, at age 2 years onwards, the retention of all harvest residues (including stem bark, branches, leaves, litter and understorey) increased the stem volume of plantations compared to complete harvest residue removal (Deleporte et al. 2008, du Toit 2008, Gonçalves et al. 2007). In *Eucalyptus grandis* in Brazil this increase was 30% at the end of the rotation (8.7 years) (Gonçalves et al. 2007). Similarly, the stem volumes of *A. mangium* in Indonesia and *A. auriculiformis* in Vietnam were, respectively, 14.7% and 10.0 % greater than those in the residue removal treatment at ages 5 and 4 years, respectively (Hardiyanto and Wicaksono 2008, Huong et al. 2008). Studies have also confirmed that the retention of post-harvest residues can increase the productivity of plantations over successive rotations (Hardiyanto and Nambiar 2014, Huong et al. 2015, Rocha et al. 2016a).

The responses of tree growth (mean annual increment (*MAI)* of stem volume over bark) to residue retention have been shown to have a strong positive relationship with the amount of residue maintained on the site after harvesting (Deleporte et al. 2008, Huong et al. 2008). The relationship between *MAI* and the amount of residue maintained on the site can be described by linear regression, with R^2=0.98, P<0.001 for *Eucalyptus* in the Congo and R^2=0.99, P<0.001 for *A. auriculiformis* in South Vietnam (Fig. 2.1) (Deleporte et al. 2008, Huong et al. 2008). Increased productivity of plantations has been clearly associated with the increased amount of nutrients contained in harvest residues which were released to the site (Nzila et al. 2002b, Shammas et al. 2003).

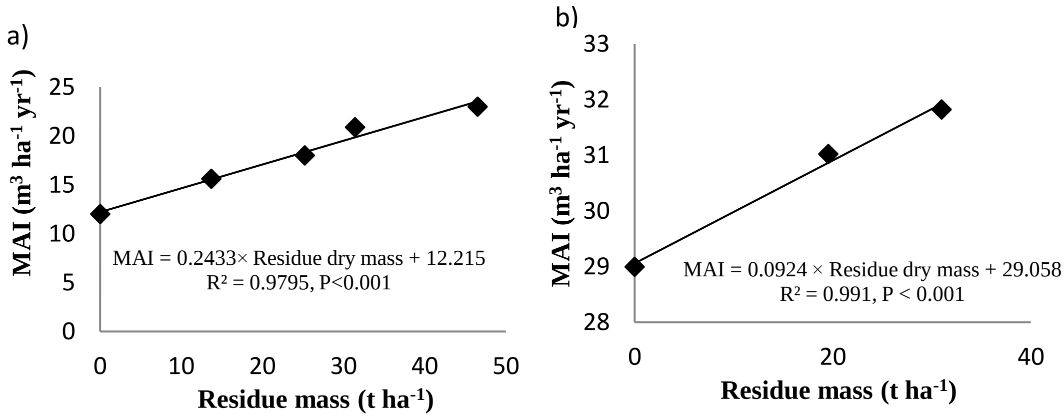

Figure 2.1. Relationship between the amount of residue maintained on the site after harvesting and productivity gained (mean annual increment of stem volume over bark (MAI)) (a) eucalypt clone in the Congo (developed from Deleporte et al. (2008)) and (b) in A. auriculiformis in Vietnam (developed from Huong et al. (2008)).

Burning residues after harvest however may result in an initial greater growth of trees compared to other residue treatments. These early growth responses have been attributed to the high amounts of nutrient rich ash after burning (Deleporte et al. 2008, du Toit et al. 2010, Gonçalves et al. 2007, Rocha et al. 2016a). The responses diminish over time (Deleporte et al. 2008, Gonçalves et al. 2007, Rocha et al. 2016a) e.g. burning increased the initial growth of plantation eucalypts in the Congo and, at 11 months after planting, the highest diameter, height and aboveground biomass were observed compared to removal, single and double residue retention treatments but at 7 years this effect of burning had reduced and the trees in the treatment where only stems had been harvested showed the greatest growth response (Deleporte et al. 2008).

The long-term effects of burning post-harvest material have been studied across *E. grandis* plantations in Brazil (Rocha et al. 2016a). At the end of the first rotation, the stem volume of *E. grandis* was similar between residue burning and residue retention (and was significantly greater than the residue removal). However, at the end of the second rotation, stem volume with residue burning was similar to residue removal and was 6% lower than residue retention (Rocha et al. 2016a).

The magnitude of tree growth responses to residue management appears to depend on site inherent characteristics (Hardiyanto and Wicaksono 2008, Mendham et al. 2008) and the quantity of residue. There were no differences in the growth of *E. globulus* between treatments where residue was retained or burnt on a highly productive red earth site in western Australia. On a low productivity grey sand site, there was a growth response to both treatments which was associated with the release of nutrients from decomposition of residue or from ash, respectively (Mendham et al. 2008). The absence of tree growth responses to residue management at a low fertility site in eucalypts in India was attributed to low amounts of residues involved (Sankaran et al. 2008) and the lack of growth responses at other sites, having a higher amount of residue, were attributed to the high inherent soil fertility (Sankaran et al. 2008). High inherent soil fertility potentially masks any nutritional benefit from harvested residues.

2.3. Effects of fertiliser application on productivity of eucalypt and acacia plantations

Maintaining the nutrient supply in soil is crucial for sustaining the productivity of plantations. The quantities of nutrient lost during harvest and site preparation may be higher than their replenishment rate especially when the rotations are short (Folster and Khanna 1997). Thus, inputs of nutrients as fertilisers will often be required for maintaining high growth rates in short-rotation plantations. However, nutrient requirements will depend on the different stages of stand development (Gonçalves et al. 2004, Gonçalves et al. 2008, Miller 1995) and inherent soil nutrient characteristics (du Toit et al. 2010, Mendham et al. 2017, Mendham et al. 2003, Sankaran et al. 2008, Viera et al. 2016). A successful nutrient management regime for sustaining productivity of plantations should be based on the balance between nutrient demand at different stages of stand development and soil nutrient characteristics.

2.3.1. Nutrient demand during stand development and types of nutrient responses of plants

The early growth of plants involves high nutrient demand (Forrester et al. 2010, Gonçalves et al. 2004, Miller 1995). Soon after planting, the tree root system develops rapidly. At this stage, competition for resources is generally low, especially without weed competition (Forrester et al. 2010, Gonçalves et al. 2004). The factors that may negatively impact early tree growth include physiological constraints caused by temperature, drought stresses or by soil factors that physically limit root development (Gonçalves et al. 2008). During the first few months after planting, trees generally allocate a large proportion of photosynthates and nutrients to root growth to explore available water and nutrients in the soils (Gonçalves et al. 2004). When the root system is more developed, trees usually receive sufficient nutrients and water from the soil for shoot growth and photosynthates are reallocated to leaf development for maximising light capture and carbon fixation (Gonçalves et al. 2004). During this stage, a sufficient supply of nutrient and water will maximise photosynthesis activity, resulting in rapid development of the canopy (Nambiar et al. 1984). Thus responses of tree growth to fertiliser application are generally observed in this stage (Forrester et al. 2010, Gonçalves et al. 2004, Melo et al. 2016, Mendham et al. 2017, Miller 1995) and are generally associated with increases in LAI (Smethurst et al. 2003) and a shift in carbon partitioning from below- to above-ground stand components (Gonçalves et al. 2004).

After canopy closure, trees fully develop their canopy (Miller 1995). When the canopy is fully developed the LAI generally stabilises for a short period before declining (du Toit 2008). The current annual increments also typically decline at this stage (Almeida et al. 2007) and the increase in wood volume is the main driver of nutrient accumulation in the stand (Gonçalves et al. 2004, Miller 1995). Trees generally require fewer nutrients at this stage than during canopy development period (Forrester et al. 2010, Miller 1995) and light and water rather than nutrients may become more limiting to growth (Forrester et al. 2010, Gonçalves et al. 2004, Miller 1995).

Fast growing species generally require high nutrient demand, especially during stand development stage. According to Laclau et al., (2003), the highest nutrient demand by *Eucalyptus* clonal Stands in Congo occurred at age two years following plating with annual requirement for N, P, K, Ca and Mg being approximately 140, 18, 58, 40 and 40 kg ha^{-1} per year (Laclau et al., 2003). Subsequently, the highest quantities of N, P, K, Ca and Mg uptake from the soil at age two years were 82, 10, 28, 43 and 38 kg ha^{-1} per year (Laclau et al., 2003). In Sumatra, Indonesia, the peak of nutrient demand by *A. mangium* also occurred between years 1 and 2 (Hardiyanto and Nambiar, 2014). The highest annual demand for N and Ca were approximately 180 and 100 kg ha^{-1} per year at age 2; while the highest demand for P, K and Mg were 8, 95 and 27 kg ha^{-1} per year at age 1 (Hardiyanto and Nambiar 2014). The above results indicate that fast growing species like acacia and eucalypt generally require high quantity of macronutrient during stand development stage (after planting until age 3), subsequently high nutrient uptake from the soil during this stage is expected.

Depending on the stage of stand development and the inherent fertility of the site, the response of plantations to fertiliser has been divided into two types (type 1 and type 2 responses) (Forrester et al. 2010, Gonçalves et al. 2008, Snowdon 2002). In most cases, responses to fertiliser are not sustained (type 1 response) (Forrester et al. 2010, Gonçalves et al. 2008, Jourdan et al. 2008). The Type 1 growth response to fertiliser occurs in the early stages following fertiliser application and then the response decreases over time and depending on the length of rotation, are minimal or non-existent at harvest (Gonçalves et al. 2008). The type 2 is where the growth response increases over the rotation and is most often observed on highly depleted soils (Gonçalves et al. 2008, Snowdon 2002).

Growth responses to fertilisation that occur after canopy closure are likely to happen if the LAI of stand is reduced via insect defoliation, pruning or thinning (Gonçalves et al. 2004).

2.3.2. Responses of eucalypt and acacia plantations to fertiliser

2.3.2.1. Responses to phosphorus (P)

Applying P fertiliser is common practice in short-rotation plantation forestry, and often associated with increased productivity in both eucalypt and acacia plantations (Hardiyanto and Wicaksono 2008, Huong et al. 2015, Judd et al. 1996, Melo et al. 2016, Mendham et al. 2017, Xu et al. 2001). In P deficient soils with low P mobility due to a high P-fixing capacity, it is important that the application of P fertiliser increases the concentration of soil solution P in a small volume of soil close to the roots soon after planting (Gonçalves et al. 2004). Thus applying P fertiliser in planting holes or spot placement of P about 10 cm from the seedling within a month of planting is common practice (Gonçalves et al. 2004).

As acacias are N-fixing species, they are generally considered to have a reduced requirement for N and an increased requirement for P compared to non-leguminous species (Ingestad 1980). For example, Scowcroft and Silva (2005) found increasing responses of *Acacia koa* up to an application of 1400 kg P ha^{-1} in Hawaii although responses varied across sites. In Indonesia, significant responses of *A. mangium* to 26–78 kg P ha^{-1} applied at planting were observed up to 30 months in South Kalimantan (Turvey 1996).

Although eucalypts are generally efficient scavengers and utilisers of P (Grove et al. 1996), strong responses to P applied at planting have also been observed (Judd et al. 1996, Melo et al. 2016, Xu et al. 2001,2002, Xu et al. 2005). *E. globulus* in southern China was found to increasingly respond to additional rates of P applied at planting with 200 kg P ha^{-1} at planting being recommended, increasing the stand volume by 750% in relation compared to the nil-P fertiliser treatment (Xu et al. 2005). Early growth responses of eucalypts to P fertiliser applied at planting has been reported (Melo et al. 2016, Xu et al. 2002) however varies across sites (Melo et al. 2016, Sankaran et al. 2008), and appears related to the existing soil P concentration (Judd et al. 1996, Melo et al. 2016, Xu et al. 2001, Xu et al. 2005). In Brazil *E.* hybrid (*E. grandis* × *E. urophylla* and *E. urophylla* × *E. globulus*) at a site with a low soil P-resin of 1.4 mg kg^{-1}, as P fertiliser application at planting was increased from 13 – 40 kg ha^{-1}, the volume increased. There was no response to P fertiliser when soil P-resin was higher (8.7 mg kg^{-1}) (Melo et al. 2016). At sites in China, the diameter and height of *E. urophylla* and *E. globulus* also responded positively up to age 3 years to P fertiliser applied at planting. The optimum rates of application for volume production appeared closely correlated with soil Bray extractable P values i.e. 200 and 40 kg P ha^{-1} for Bray extractable P (Bray I) values of 1.5 mg kg^{-1} and 8.7 mg kg^{-1}, respectively (Xu et al. 2001). For *E. globulus* at several sites in Australia where Bray extractable P (Bray I) ranged from 7.1 to 26.7 mg kg^{-1}, scaled quantities of P applied at 9 months up to 50 kg ha^{-1} for the lowest P value led to gains in volume (Judd et al. 1996). In comparison, in acacia plantations in Vietnam (Beadle et al. 2013) and in Indonesia (Mendham et al. 2017) there was no relationship between the observed growth responses to P and site soil Bray I extractable P.

The responses of eucalypt and acacia plantations to P fertiliser are linked with stages of stand development. Early growth of plants requires large amounts of nutrients to rapidly develop root and leaf biomass, tissues where nutrients are stored at high concentrations (Miller 1984, Miller 1995). P plays a crucial role in the chemical structure of adenosine triphosphate (ATP), hence the high demand and uptake of this nutrient at this time (Melo et al. 2016) e.g. the annual demand for P in a short-rotation *E. grandis* plantation in Brazil was greatest in the first year (Leite et al. 2011). Similarly, growth responses by *A. mangium* to P fertiliser applied at planting in south Sumatra in Indonesia were greatest in the first year, with an average rate across sites of 23, 5.1 and 2.7 kg P ha^{-1} at ages 1, 1.5 and 3 yr, respectively (Mendham et al. 2017), which was linked with the peaked P accumulation by this species at age 1 year (Hardiyanto and Nambiar 2014).

Since eucalypts and acacias generally respond to P fertiliser in the early stages it can be used to stimulate rapid early establishment but growth responses tend to decline with time (Hardiyanto and Nambiar 2014, Leite et al. 2011, Melo et al. 2016, Mendham et al. 2017, Xu et al. 2005). This decreasing response to P fertiliser application has been linked to the extending root system accessing increasing amounts of resident soil P (Novais et al 1986 cited in Melo et al. (2016). In addition, when responses to fertiliser occur, crown development leads to an increase in LAI (Smethurst et al. 2003), which results in the faster development of intraspecific competition because of the greater between-tree competition for light and water (Gonçalves et al. 2004). The decreasing response of eucalypts to P fertiliser at later stages of stand development has been observed in many studies (Melo et al. 2016, Xu et al. 2001,2002, Xu et al. 2005).

P management may become crucial over multiple rotations for sustaining the productivity of acacia. For example, Huong et al. (2015) found that under second rotation *A. auriculiformis* in South Vietnam available P (Bray I) declined by 5 kg ha^{-1} (from 12 to 7 kg ha^{-1}) at about age 3 years. Similarly, a steady reduction in extractable P (Bray I) was found over a 7 year period (from 3.2 mg kg^{-1} to 1.7 mg kg^{-1}) at a second rotation *A. mangium* site in South Sumatra (Hardiyanto and Nambiar 2014).

2.3.2.2. Responses to nitrogen (N)

Nitrogen is also a key limiting nutrient in many environments due to the requirement by trees to produce large quantities of biomass, relative to available N accessible in the soil (Sankaran et al. 2005). Acacias, in partnership with *Bradyrhizobium* species, have a high capacity to fix nitrogen from the atmosphere (Wibisono et al. 2015). Therefore, acacias do not generally respond to nitrogen fertiliser (Hardiyanto and Wicaksono 2008). In contrast, responses of eucalypts to N has been observed in many studies (Albaugh et al. 2015, Melo et al. 2016, Mendham et al. 2015, Smethurst et al. 2003, Xu et al. 2005) but responses of plantations to N will depend on the inherent fertility of soils (Gonçalves et al. 2004, Gonçalves et al. 2008).

In tropical and subtropical regions, fast-growing short rotation eucalypt plantations do not usually respond to N fertiliser during the first rotation as the N in soil is sufficient (Gonçalves et al. 2008). However, large amounts of N are exported from plantation forests, especially after clear fell harvesting (Achat et al. 2015, Huong et al. 2015, Sankaran et al. 2005). There is a possibility that the reserves of mineralisable organic N will have been depleted even after one rotation (Gonçalves et al. 2008) and that trees will respond to N fertiliser after one or more rotations (Melo et al. 2016, Sankaran et al. 2008, Xu et al. 2008). For example, in the Congo, examining input-output budgets at the ecosystem level suggested that increasing N fertiliser applications are required over successive rotations to sustain productivity of eucalypt plantations (Laclau et al. 2005). A response to N is most pronounced on sites with low soil organic matter (Laclau et al. 2005), and N deficiency may even be observed during the first rotation (Gonçalves et al. 2008). Hence, practices that can enhance the stocks of soil organic N should be encouraged for sustaining productivity of plantations.

Planting species of nitrogen fixing such as acacia with eucalypts or alternating such species in successive rotations has been shown to enhance soil organic matter and soil N (Folster and Khanna 1997, Forrester et al. 2013, Laclau et al. 2008, Mendham et al. 2015) and reduce the required amounts of N fertiliser inputs. Legume species are likely to increase the deposition of organic matter production at the soil surface and to delay the decomposition of soil C, an effect related to the low C:N ratio of their organic residues (Gonçalves et al. 2008). In mixed-species plantations of *Eucalyptus globulus* (E) and *Acacia mearnsii* (A) in Australia, Forrester et al. (2013) found that soil organic matter was higher in all treatments that contained *A. mearnsii*, peaking in the mixtures of 50E:50A. In alternating species system in Indonesia, Mendham et al. (2015) found that *Eucalyptus pellita* and hybrids respond significantly to N fertiliser at planting when planted in ex-eucalyptus sites, but not in ex-acacia sites. While mixed-species are not a common practice in commercial plantation in S-E Asia, the alternating species regimes may provide an option for nutrient management to sustain site fertility and the productivity of acacia and eucalypt plantations while minimising the costs of nitrogen fertiliser inputs.

2.3.2.3. Responses to potassium (K)

Potassium is an essential element for enzyme activation, protein synthesis and photosynthesis of plants. It is a highly mobile charge carrier and has an important role in osmoregulation during cell expansion and stomatal movements (Almeida et al. 2010, Battie-Laclau et al. 2014). Potassium has been identified as one of the key nutrients limiting growth of eucalypts in subsequent rotations in Brazil (Almeida et al. 2010). K application also plays a crucial role for improving productivity of eucalypt plantations, especially under drought conditions. In plantation *E. grandis* on highly weathered tropical soils, application of K increased tree growth, wood production, leaf gas exchange, stomatal sensitivity to water deficit of trees and water use efficiency (Battie-Laclau et al. 2014).

Responses of growth to K fertiliser at planting were not observed in the first rotation of eucalypt plantation in Brazil (Melo et al. 2016), but were observed in the subsequent rotation, especially at sites with low natural chemical fertility and soil water content (Almeida et al. 2010, Battie-Laclau et al. 2016, Melo et al. 2016). In 4 year old clonal *E. grandis* × *urophylla* and *E. urophylla* × *globulus* planted across different sites representing the different growing conditions in Brazil, the rates of K fertilisation for optimal volumetric gains ranged from 104 – 184 kg ha^{-1} (Melo et al. 2016). According to these authors, the responses of eucalypts to K depended on available soil K and soil water content with the highest responses being found at sites with the lowest available K and the lowest soil water content.

Harvesting of fast-growing acacia plantations is associated with the export of large amounts of K from a site (Hardiyanto and Nambiar 2014, Huong et al. 2015). For example, harvesting the first rotation of *A. auriculiformis* (age 7 years) in South Vietnam resulted in the removal of 82 kg ha^{-1} of K; the loss was increased to 156 kg ha^{-1} of K in the second rotation (6 years) (Huong et al. 2015). Despite the large potential export of K from acacia plantations and its depletion at a site, addition of K fertiliser at planting and at ages 26 and 33 months had no effect on growth of *A. mangium* plantations in Sumatra, Indonesia (Hardiyanto and Wicaksono 2008).

2.3.2.4. Methods for applying of N, P and K fertiliser

In P deficient soils with low P mobility due to a high capacity to fix P, it is important that P fertiliser application should be ensure to increase the concentration of soil solution P in at least a small volume of soil close to the roots soon after planting (Gonçalves et al. 2004). Thus applying P fertiliser in planting holes at planting or spot placement of P about 10 cm from the seedling within a month of planting is generally applied (Gonçalves et al. 2004).

In contrast, due to high mobility of N and K (mostly by mass flow), the high permeability and the low CEC of the majority tropical soils, the application of these nutrients should be split into two or more times (Gonçalves et al. 2008). In addition, the time of application should coincide with the larger nutritional demand, in such a way to increase the fertiliser use efficiency.

2.4. Management of forest health for sustaining the productivity of plantations

There are various factors which can influence forest health. These factors can be identified as abiotic factors e.g. climate, fertilisation, overstocking, poor site or species matching and low diversity and biotic factors e.g. microbial communities in the soil, weeds, insect pests and pathogens. Abiotic and biotic disturbances have large impacts on the health and vitality of natural and planted forest which can lead to substantial economic and environmental losses (Dell et al. 2012, Jactel et al. 2009, Stone 2001). In planted forest biotic factors impact all stages of the rotation, affecting tree growth, survival, yield and quality of wood and non-wood products (Mohammed et al. 2012, Pinkard et al. 2011, Prudic et al. 2005, Thu et al. 2012).

2.4.1. Abiotic factors

In the review of managing threats to the health of tree plantations in Asia, Dell et al. (2012) concluded that site condition is one of abiotic factors that driver tree health and productivity of eucalypt and acacia plantations. Major soil fertility constraints for sustaining productivity of eucalypt and acacia plantations were presented in Dell et al.

(2012). Overall, macronutrient deficiencies are becoming less common because application of fertiliser in plantations is common practice nowadays. In contrast, micronutrient deficiencies are an ongoing problem as their symptoms are common, and are not well managed (Dell et al. 2012, Dordas 2008, Nambiar and Harwood 2014). In addition, micronutrient disorders can be induced by macronutrients via fertilization inputs (Dell et al. 2012). Both eucalypts and acacias are particularly sensitive to B deficiency which leads to the loss of crown vigour, shoot death, poor stem form and bunchy canopies. This situation was found in many parts of Asia, including China, Indonesia, Lao, Philippines, Thailand and Vietnam (Dell et al. 2012).

2.4.2. Biotic factors

Many manuals of damage symptoms caused by known pests and pathogens have been published (Old et al. 2003, Old et al. 2000, Stone et al. 2003, Thu et al. 2010). Growing mostly in a non-native environment, the productivity of hardwood plantations in SE Asia is increasingly threatened by insect pests and pathogens (Crous et al. 2017, Dell et al. 2012, Wingfield et al. 2015). As the plantation estate expands, there are more opportunities for native insect pests and pathogens to jump to acacia and/or eucalypts (Crous et al. 2017, Dell et al. 2012, Wingfield et al. 2015). In Sumatra, Indonesia, Harwood and Nambiar (2014) reported that growth rates of *Acacia mangium* have been reduced from 22-25 to less than 15 m^3 ha^{-1} $year^{-1}$ as a result of fungal diseases (*Ganoderma* and *Ceratocystis*). In both Vietnam and Malaysia, *Ceratocystis* is considered an extreme threat to acacia, with tree mortality rates up to 20% in some acacia plantations in Vietnam (Thu et al. 2012). Serious biotic damaging agents of eucalypts in SE Asia are a gall wasp *Leptocybe invasa*, a bacterial wilt pathogen *Ralstonia solanacearum* and the fungal leaf and stem blight pathogens *Calonectria quinqueseptata* and *Cryptosporiopsis* *eucalypti* (Dell et al. 2012, Thu 2016). Tropical acacias and eucalypts are also affected by termites (Calderon and Constantino 2007, Ngoc et al. 2011), with up to 30% of seedlings being infested in many young acacia and eucalypt plantations across Vietnam (Ngoc et al. 2011). It is very difficult to predict what known insect pests or diseases may become problematic in the future, climate change makes this even more challenging (Dell et al. 2012, Pinkard et al. 2011, Wingfield et al. 2015). Often there is limited knowledge of the biology of most pest and pathogen species and their interactions with an acacia or eucalypt host (Dell et al. 2012).

For sustaining the productivity of hardwood plantations, existing and potential abiotic and biotic threats need to be an integrated part of the management system (Crous et al. 2017, Dell et al. 2012, Pinkard et al. 2011, Wingfield et al. 2015) as they interact in their impact on plantation health, especially with climate variability and change (Bebber et al. 2014, Moore and Allard 2008). A field manual for using the crown damage index (CDI) developed by Stone et al. (2003) for pest and disease assessment in young eucalypt plantations has provided a useful guideline for assessment of both abiotic and biotic factors.

2.4.3. Effect of silvicultural practices on plantation health

There has been limited studies linking plantation health to silvicultural practices (Jactel et al. 2009). In Australia, Pinkard et al. (2006) found that fertiliser application as N or N + P can improved crown health and productivity of a three-year-old *E. globulus* plantation which suffered from the Eucalypt weevil (*Gonipterus scutellatus*). Residue management has been found to influence community structure of invertebrate pests in wattle (*Acacia mearnsii*) plantations in South Africa with a greater infestation of soil invertebrate pests on sites where the plantation residue was windrowed–burnt–weeded or ‘broadcast’ (20.34%) than in the other treatments (windrowed–burnt–ripped or fallow; 2.36%)

(Govender 2014). Hence, effect of silvicultural treatments to be trialled on potential biotic damage should be taken into account in any experimental design.

2.5. Summary

The review has shown that the inter-rotational phrase of short-rotation plantations may be a crucial time and that the right silvicultural interventions during this period can potentially maintain and even increase the productivity of the plantations. Current research has focused on examining the effect of inter-rotational practices including harvesting, residue management and fertiliser application on site properties and the productivity of eucalypt and acacia plantations. The outcomes of these studies vary between species and sites. More research is required to understand the effect of these practices on the productivity of a particular species and landscape.

CHAPTER 3

CONTRIBUTION OF HARVEST RESIDUES TO NUTRIENT CYCLING IN A TROPICAL *ACACIA MANGIUM* WILLD. PLANTATION

Article reference:

Bich, N.V., Eyles, A., Mendham, D., Dong, T.L., Ratkowsky, D., Evans, K.J., Hai, V.D., Thanh, H.V., Thinh, N.V., Mohammed, C. Contribution of harvest residues to nutrient cycling in a tropical *Acacia mangium* Willd. plantation.. *Forests* 9 (9): 577e.

CHAPTER 3. CONTRIBUTION OF HARVEST RESIDUES TO NUTRIENT CYCLING IN A TROPICAL *ACACIA MANGIUM* WILLD. PLANTATION

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This chapter was published in Forests – an Open Journal of Forestry, vol. 9 (9): 577.

Abstract:

Harvest residues can play a crucial role in conserving nutrients for recycling in forests, but little is known about the rates of decomposition and nutrient release from these residues following logging in tropical acacia plantations. In this study, we examined the biomass and nutrient content of harvest residue components (bark, leaves and branches) using the litterbag technique for a 1.5-year-period following harvest of a 7-year-old *Acacia mangium* plantation in northern Vietnam. At harvest, the total dry biomass of harvest residues was 18 t ha^{-1} comprising bark (8.9 t ha^{-1}), branches (6.6 t ha^{-1}) and leaves (2.5 t ha^{-1}). The retained bark on site conserved 51% N, 29% P, 32% K, 64% Ca and 24% Mg content from harvest residues for recycling. Decomposition rate of the leaves was the most rapid (k = 1.47 $year^{-1}$; $t_{0.5}$ = 0.47 year), then branches (k = 0.54 $year^{-1}$; $t_{0.5}$ = 1.29 year) and bark (k = 0.22 $year^{-1}$; $t_{0.5}$ = 3.09 year). During decomposition, the loss of nutrients from harvest residues was K ≈ Ca > N > P> Mg. Decomposition of harvest residues and the associated rate of nutrient release can potentially supply a significant amount of nutrients required for stand development in the next rotation.

Keywords: nutrient loss, mass loss, nutrient release, nutrient dynamics, decay constant, residue half-life, nutrient cycling, tropical plantation

3.1. Introduction

In Vietnam, plantations are typically clear-felled at the end of the rotation. The stemwood down to 3 cm in diameter (over bark) is exported from the site as harvest product (Hai et al. 2009b, Huong et al. 2015). Bark is often removed from the site with the commercial logs, and sold for the production of charcoal, tannin and garden compost (Anh 2013, Bac 2013, BGDT 2015), or stripped after harvesting at the edge of the site or in a nearby wood yard, and not distributed over the logging area. The non-commercial logs and branches may be collected by locals for firewood, and the site subsequently burnt (Nambiar et al. 2015). There are concerns that these practices may degrade the productive potential of the site over successive rotations (Goncalves et al. 2013, Laclau et al. 2010, Nambiar et al. 2015, Rocha et al. 2016a). While burning can improve soil fertility, at least initially, it can also lead to large losses of N via volatilisation (Deleporte et al. , Gonçalves et al. 2007, Mendham et al. 2003, Raison et al. 1993), and P, Ca and K through leaching, as well as water and wind erosion (Giardina et al. 2000, Gonçalves et al. 2007, Raison et al. 1985a). Retention of harvest residues, especially bark, acts to conserve nutrients and leads to their controlled release in a way that minimises losses from leaching and potentially supplies the amount of nutrients required for stand development in the next rotation (de Souza et al. 2016, Ferreira et al. 2016, Hernández et al. 2009, Rocha et al. 2016b, Shammas et al. 2003). Hence, understanding decomposition rates and nutrient release from harvest residues, including bark, is important for informing residue and nutrient management over successive rotations.

Management of residues after harvesting has been shown to improve site fertility (Achat et al. 2015, Gonçalves et al. 2007, Hardiyanto and Nambiar 2014, Nambiar et al. 2015, Versini et al. 2014). For example, retention of harvest residues, including bark, branches and leaves of a *Eucalyptus grandis* Hill ex Maiden plantation in Brazil resulted in soil organic carbon (TC) and soil nitrogen (TN) (0–5 cm soil depth) that were 33% and 43% higher, respectively, seven years after establishment than when all harvest residues were removed (Gonçalves et al. 2007). Similarly, TC and TN (0–10 cm soil depth) increased by 17% and 11%, respectively, in a two-year-old *A. mangium* plantation in Sumatra, Indonesia when harvest residues were retained rather than removed (Hardiyanto and Nambiar 2014). This is because decomposing harvest residues can provide a significant source of nutrients to the soil (Hernández et al. 2009, Shammas et al. 2003, Versini et al. 2014). For example, harvest residues potentially contributed 176 kg ha^{-1} of N, 15 kg ha^{-1} of P and 276 kg ha^{-1} of K to soil fertility during the first year following harvest in a *Eucalyptus globulus* Labill. plantation in western Australia (Shammas et al. 2003), and 176, 20, 375, 460 and 92 kg ha^{-1} of N, P, K, Ca and Mg, respectively, during the first 2 years following harvest in a *Eucalyptus dunnii* Maiden plantation in Uruguay (Hernández et al. 2009). Retention of harvest residues, therefore, can conserve nutrients for recycling.

Fast-growing short-rotation plantation species generally require large amount of nutrients to optimize yield (Folster and Khanna 1997). The amount of nutrient uptake by tropical acacia trees is generally highest during the first three years after planting (Hardiyanto and Nambiar 2014, Huong et al. 2015); approximately 180, 7, 80, 90 and 23 kg ha^{-1} year^{-1} of N, P, K, Ca and Mg, respectively, were accumulated in the above-ground stand biomass of *A. mangium* at age two years (Hardiyanto and Nambiar 2014). Although the demand for P appears to be low, in Vietnam, plantation soils are characteristically very low in soil P (Dong et al. 2014, Huong et al. 2015, Sam and Binh 2001) and most forest growers can only afford to apply a small dose of fertilizer at planting (Dong et al.

2014, Hung et al. 2016, Nambiar et al. 2015). As P deficiency could be a concern in successive rotations of acacia (Hardiyanto and Nambiar 2014, Huong et al. 2015), retention of harvest residues may provide a sufficient source of P as well as other nutrients which, given the limited soil nutrient pool, could support a demand that results in commercial rates of growth.

Harvesting of short-rotation plantations can be associated with the export of large quantities of organic matter and nutrients from the site (Achat et al. 2015, Folster and Khanna 1997, Huong et al. 2015). For example, removal of stemwood without bark from a six-year-old *Acacia auriculiformis* A. Cunn. ex Benth. plantation in southern Vietnam, led to the export of 135.2, 47.3, 115.3, and 15.7 kg ha^{-1} of N, P, K, and Ca, respectively (Huong et al. 2015). Retention of bark on-site is potentially important, with the quantities of nutrients extracted by harvesting increasing to 256.5, 55.7, 155.6, and 41.1 kg ha^{-1} of N, P, K and Ca, respectively, in the same plantation if stemwood with bark had been removed. Similarly, in a 10-year-old *A. mangium* plantation in Sumatra, Indonesia, harvesting stemwood, with rather than without bark would have increased the export of N, P, K, Ca and Mg by 55%, 15%, 52%, 97% and 48%, respectively (Hardiyanto and Nambiar 2014). Although the bark of acacia trees represents only 9%–10% of the total stand AGB when the trees are harvested, in the above studies it contributed 19%–24% of N, 7%–11% of P, 15%–17% of K, 30%–36% of Ca and 7%–15% of Mg (Hardiyanto and Nambiar 2014, Huong et al. 2015). As debarking on site at harvesting can substantially reduce the export of nutrients (Hardiyanto and Nambiar 2014, Huong et al. 2015), the retention of bark and its even distribution across the site may potentially reduce the costs of fertilizer application in the next rotation.

Given that decomposition and nutrient release from plant materials are largely influenced by environment (Meentemeyer 1978) and substrate quality (Ge et al. 2013, Krishna and Mohan 2017, Murphy et al. 1998), materials of lower nutrient content generally decompose more slowly, immobilize more nutrients during decomposition and have slower rates of net mineralization than nutrient-rich materials (Vitousek 1982). Acacias are a N-fixing species, and therefore the concentration of N in a given material is generally higher in acacias than in other genera such as eucalypts (Bachega et al. 2016, Tchichelle et al. 2017). This may lead to different activities of microbial decomposers, and thus rates of decomposition and nutrient release. As little is known about the dynamics of nutrient release from the decomposition of acacia harvest residues, particularly bark residue (Bachega et al. 2016, Hardiyanto et al. , Ngoran et al. 2006, Tchichelle et al. 2017), it is crucial to measure rates of decomposition and nutrient release from its various components, especially in tropical environments where the area of acacia plantation estates has grown rapidly.

Acacia plantations including *A. mangium*, *A. auriculiformis* and their hybrid currently represent a significant proportion of the commercial forest in Vietnam (Harwood and Nambiar 2014) and are managed on a rotation length of 5–8 years for both pulp and timber production (Nambiar et al. 2015). Most of the resource is currently in the second and third rotation, and their productivity varies from 10 to 25 m^3 ha^{-1} $year^{-1}$ (Hung et al. 2016, Nambiar et al. 2015) depending on site condition as well as management inputs. Sustaining the productivity of these plantations will rely on maintaining, and if possible increasing, the nutrient capital of the current forestry land base (Harwood and Nambiar 2014, Nambiar et al. 2015). The objectives of this study were to evaluate the contribution of harvest residues, particularly the bark component, to nutrient cycling in these intensive short-rotation plantation systems. To this end, decomposition rates of harvest residues of *A. mangium* were quantified. The results from this study are expected to assist with optimizing residue management of short-rotation tropical acacia plantations.

3.2. Materials and Methods

3.2.1. Location and Site Description

The study site was located at Phuc An commune in the Yen Binh district of Yen Bai province in northern Vietnam, (21°51'N, 105°00'E; 100 m above sea level). The climate is tropical with four distinct seasons. During the study period, the mean monthly temperatures ranged from 15 to 28℃ (average 22°C), and the mean monthly rainfall ranged from 6.1 to 375 mm (average 144 mm) (Fig. 3.1).

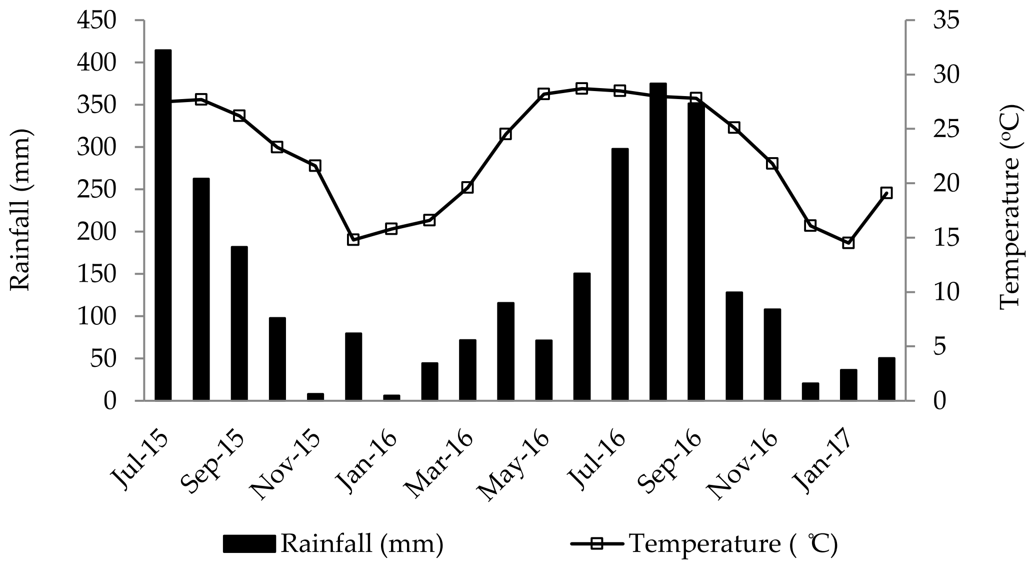

Figure 3.1. Average monthly temperatures (*continuous line*) and monthly rainfall (*vertical bars*) at Yen Bai weather station, 40 km from the site during the experimental period.

The site is characterized by steep slopes that range from 10° (at the top of the hill) to 30°–40° (in the middle and at the bottom of the hill). The soil is classified as a Ferric (Ferralic) Acrisol (FAO 1998) with a depth of ~0.5 m (in the middle and bottom of the hill) to 1 m (on top of the hill). The topsoil (0–10 cm depth) is acidic with a pH (1:5 water) of 3.8, a Bray II extractable P of 4.04 mg kg^{-1} and soil organic carbon (TC) of 44 g kg^{-1} (Table 3.1). A more detailed description of soil properties is provided in (Bich et al. 2019b).

Table 3.1. Soil chemical properties at the experimental site in northern Vietnam. Standard errors are shown in parentheses (n = 5).

Soil depth	**pH**	**Soil organic matter**	**Total N**	**Total P**	**Bray II extractable P**	**Exchangeable cations [cmol$_c$ (+) kg^{-1}]**		
(cm)	**(1:5 water)**	**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**	**mg kg^{-1}**	**K**	**Ca**	**Mg**
0-10	3.79	44.36	2.10	0.09	4.04	0.12	0.70	0.45
	(0.03)	(2.57)	(0.09)	(0.00)	(0.51)	(0.01)	(0.11)	(0.09)
10-30	3.94	27.80	1.54	0.08	2.21	0.08	0.57	0.40
	(0.08)	(2.14)	(0.07)	(0.00)	(0.37)	(0.02)	(0.13)	(0.07)

In the 1980s, the area was converted from secondary forest (degraded natural forest) to a native tree plantation of *Styrax tonkinensis* (Pierre) Craib. Two successive rotations of *A. mangium* were then planted in 2000 and 2008. The second rotation was planted at a spacing of 2 m × 2.5 m and mixed NPK fertilizer (17 kg ha^{-1} N, 15 kg ha^{-1} P and 8 kg ha^{-1} K) was applied at planting. At harvesting in April 2015, trees were aged 7 years and had a mean annual increment (MAI) of 13.3 ± 2.3 m^3 ha^{-1} year^{-1} based on measurements made on surface area rather than horizontal-projected area (noting that the horizontal projected area is less than the ground surface area because of the slope of the plots). The total aboveground stand biomass (AGB) was 60.8 t ha^{-1}, comprising stemwood (70%), bark (15%), branches (11%) and leaves (4%). Total nutrient content accumulated in aboveground components was 533.9, 16.5, 46.5, 314.3 and 9.1 kg ha^{-1} of N, P, K, Ca and Mg, respectively. The understorey vegetation was high and dense, and dominated by woody shrubs and some grass.

3.2.2. Estimation of Biomass and Nutrients in Harvest Residues, Litter and Understorey Vegetation

In February 2015, 16 representative plots of 750 m^2 were established to determine stand growth and biomass accumulation in the second rotation. Height (H, m) and diameter (DBH, cm) at breast height (1.3 m) of all trees in the plots were measured. A total of 30 trees, covering the range of five diameter classes i.e. 6–9, 10–13, 14–17, 18–21, and 21–24 cm (six trees per diameter class), were randomly sampled for each diameter class to develop predictive models for calculating the biomass and nutrient content of the stand. The method for measuring the components of stand biomass is described in Huong et al. (2015). Briefly, after felling the tree, DBH and H (to a top end diameter of 3 cm) were measured. The tree was divided into five equal-length sections based on the tree height up to 3 cm in diameter over bark. Fresh biomass of stemwood, stem bark (manually stripped), branches and leaves were weighed at the site and subsamples were then dried to a constant weight at 65 °C.

Forest floor litter and understorey vegetation were assessed by sampling all biomass within five randomly located quadrats (16 m^2) in each plot. Litter was separated into woody (branches, stemwood plus bark) and non-woody (leaves, reproductive parts) materials, and the understorey into woody and non-woody plants. Each part of the material (woody or non-woody) of the litter and understorey vegetation component was weighed and a combined subsample of about 200 g from each part (woody or non-woody) of the components was selected for each plot (total of 32 subsamples per component). The subsamples were oven-dried at 65 °C to a constant weight.

The dry mass:fresh mass ratio of tree, litter and understorey components was used to calculate the total dry mass of each component. Subsamples of biomass components from two trees per diameter class (a total of ten trees) and of litter (16 subsamples of each woody and non-woody part) and understorey vegetation (16 subsamples of each woody and non-woody plants) were ground to 0.02 mm particle size for nutrient analyses.

To estimate the biomass of harvest residue components, allometric relationships (equations) between DBH and biomass components of living trees were established (see Supplementary Fig. 3. S1) for bark ($y = 0.0208 \times DBH^{2.3914}$, $r^2 = 0.92$), branches ($y = 0.0044 \times DBH^{2.8555}$, $r^2 = 0.81$) and leaves ($y = 0.0020 \times DBH^{2.7966}$, $r^2 = 0.89$). Based on the allometric equations, biomass components were estimated for each individual tree in sample plots, and were then summed to give plot totals and then expressed as total biomass per ha.

3.2.3. Rate of Decomposition and Nutrient Release of Harvest Residues (Branches, Leaves and Bark)

The experimental site was initially established in a third rotation *A. mangium* plantation in June 2015 to examine the effect of residue management treatments and fertilizer application at planting on growth and soil properties. The details of the experimental design are presented in Bich et al. (2019b). In brief, the design was 20 plots based on a randomised complete block design with five replications. Each replicate occupied a similar position in the landscape, with plots grouped according to elevation: top-hill, middle-hill and bottom-hill. This study used only the five plots that combined residue retention and fertiliser as 17 kg ha^{-1} of N, 15 kg ha^{-1} of P and 8 kg ha^{-1} of K (applied as 200 g of NPK: 5:10:3 fertiliser per tree) applied in the base of the planting hole at planting. All harvested stemwood without bark down to 3 cm in diameter over bark had been exported from the site. All other harvested tree components, bark, branches and leaves, and forest floor components were retained as residues and distributed evenly across the site prior to application of treatments. Each plot contained 6 × 6 trees and was surrounded by two rows of buffer trees. Trees had a spacing of 2.5 m × 3 m (1,333 trees ha^{-1}).

Decomposition of harvest residues from the *A. mangium* stand excluding litter and understorey vegetation was measured by the mesh bag method (Bärlocher 2005). Briefly, 10 kg samples each of fresh leaves, branches (< 3 cm in diameter, ~10 cm lengths) and bark were collected randomly across the site immediately after clear-felling in April 2015 and air-dried at room temperature. The mesh bags, 30 cm × 28 cm in size with 2-mm mesh were used to minimise leakage of small fragments while allowing access by decomposer organisms (O'Connell 1997). Each bag was packed with the air-dried residues, either 40 g leaves, 100 g bark or 100 g branches. Additional samples were oven dried at 65℃ and weighed to establish moisture content and dry weight before grinding for nutrient analysis.

A total of 21 mesh bags comprising nine of leaves and six each of branches and bark were located randomly within each of the five plots (a total of 105 bags) on 25th July 2015. Bags were positioned on top of the litter layer to simulate the position and microclimate representative of the majority of the harvest residues. For the leaf component, one bag from each plot was collected every 60 days until 540 days after bags were first placed in the plot (1 sample per plot × 5 plots per collection time × 9 times = 45 samples); for the bark and branch components, one bag of each was collected every

90 days during the same period (1 sample per plot × 5 plots per collection time × 6 times = 30 samples per component). The bags were air dried, and the contents brushed free of soil, insect frass and other debris, oven dried at 65 ℃ and weighed to determine dry weight loss. Oven-dried samples were ground (≤ 0.02 mm particle size) for nutrient analysis.

3.2.4. Plant Nutrient Analysis

Oven-dried biomass samples of tree components, litter, understory, and decomposing harvest residues from mesh bags were digested in concentrated sulphuric acid with 30% hydrogen peroxide; all nutrients were measured from that digest. Total N was analyzed by Automatic Kjeldahl distillation (UDK 149, PLT Scientific SDN BHD, Puchong Selangor Darul Ehsan, Malaysia), P by spectrophotometry (Jasco 7800 spectrophotometer - JASCO International Co., Ltd, Tokyo, Japan), K by flame photometry (Model 410 Flame Photometer Range – Sherwood Scientific Ltd, Cambridge, UK), and Ca and Mg by atomic absorption spectroscopy (Berry and Johnson 1966). The initial nutrient content of each stand biomass component was calculated from nutrient concentrations multiplied by dry weight while the nutrient content of residues from the mesh bags was calculated as the product of the dry weight remaining and the relevant nutrient concentration.

3.2.5. Statistical Analysis

Long-term patterns of mass loss (up to 10 years) can be analysed by a range of decay models (Harmon et al. 2009). However, given that this decomposition study was only 1.5 years long, a single exponential decay model (Olson 1963) was used to fit the mass loss of each residue component (bark, leaves and branches) as a function of time as follows: $M_t = M_0 \times e^{-kt}$, where M_t is residue dry weight at time t, M_0 is the initial residue dry weight at time 0, *k* is exponential decay coefficient (day^{-1}), and *t* is time in days. The exponential decay equation was converted to a linear form ($\ln[M_t] = \ln[M_o] - kt$) before the regression procedures were performed. Linear regression of ln[% mass remaining] versus time *t* was used to determine the decay constant *k*; the time required for the decomposition of half of the initial residue weight ($t_{0.5}$) was then calculated as $t_{0.5} = 0.693/k$ (Olson 1963). Analysis of covariance was conducted to test whether these decomposition rates differed among leaf, branch and bark; that is, the regression lines of the three separate components were compared to see if they had the same slope. The statistical analyses were conducted with SPSS for Windows version 22.0 (IBM Corp, 2013).

3.3. Results

3.3.1. Biomass and Nutrient Content of Harvest Residues, Litter and Understorey Vegetation

The total initial dry weight of all residues (from harvest and forest floor) following logging was 27.2 t ha^{-1}, comprising 66% harvest residues and 34% forest floor (Table 3.2). The total initial amounts of N, P, K, Ca and Mg maintained on the site were 439.6, 14.8, 60.7, 185.0 and 20.1 kg ha^{-1}, respectively. Harvest residues alone accounted for 60% of N, 61% of P, 43% of K, 64% of Ca and 24% of Mg (Table 3.2).

Table 3.2. Initial dry weight and nutrient content of harvest residues and forest floor on the site following harvest of a seven-year-old *A. mangium* plantation in northern Vietnam. Standard errors are shown in parentheses (n= 16). DM is dry matter.

Components	Dry weight (t DM ha^{-1})	Nutrient content (kg ha^{-1}) N	P	K	Ca	Mg
Harvest residue components						
Bark	8.9 (0.3)	133.4 (5.2)	2.6 (0.1)	8.4 (0.3)	76.5 (3.0)	1.2 (0.1)
Branches	6.6 (0.3)	53.9 (1.8)	1.9 (0.1)	4.9 (0.1)	28.9 (1.3)	0.9 (0.1)
Leaves	2.5 (0.1)	76.0 (3.3)	4.5 (0.2)	13.1 (0.6)	13.7 (0.6)	2.8 (0.1)
Subtotal	18.1 (0.7)	263.4 (10)	9.0 (0.3)	26.4 (1.0)	119.2 (4.9)	4.9 (0.2)
Forest floor residue components						
Litter	5.8 (0.6)	128.9 (13.3)	5.1 (0.5)	31.6 (3.3)	45.4 (4.7)	13.7 (1.4)
Understorey	3.3 (0.4)	47.3 (5.6)	0.7 (0.1)	2.7 (0.3)	20.4 (2.4)	1.5 (0.2)
Subtotal	9.1 (0.6)	176.2 (12)	5.9 (0.5)	34.4 (3.1)	65.8 (4.3)	15.2 (1.3)
Total residue with bark	27.2 (0.9)	439.6 (15)	14.8 (0.6)	60.7 (3.2)	185.0 (6.3)	20.1 (1.2)
Total residue without bark	18.2 (0.7)	306.1 (12)	12.2 (0.5)	52.3 (3.1)	108.5 (4.5)	18.9 (1.3)

3.3.2. Decomposition of Harvest Residue Components

A single exponential decay model explained the decomposition of each of the harvest residue components very well (Fig. 3.2; Table 3.3). The half-lives for leaf, branch and bark dry weight were 0.47, 1.29 and 3.09 years, respectively (Table 3.3). The slopes of the regression lines indicate that the decomposition rates of bark and branches were significantly lower than that of leaves ($p < 0.05$; Fig. 3.2; Table 3.3). The decomposition of leaf dry weight was the fastest throughout the study period with only 10% remaining after 540 days as compared to 47% and 72% for branches and bark, respectively (Table 3.3).

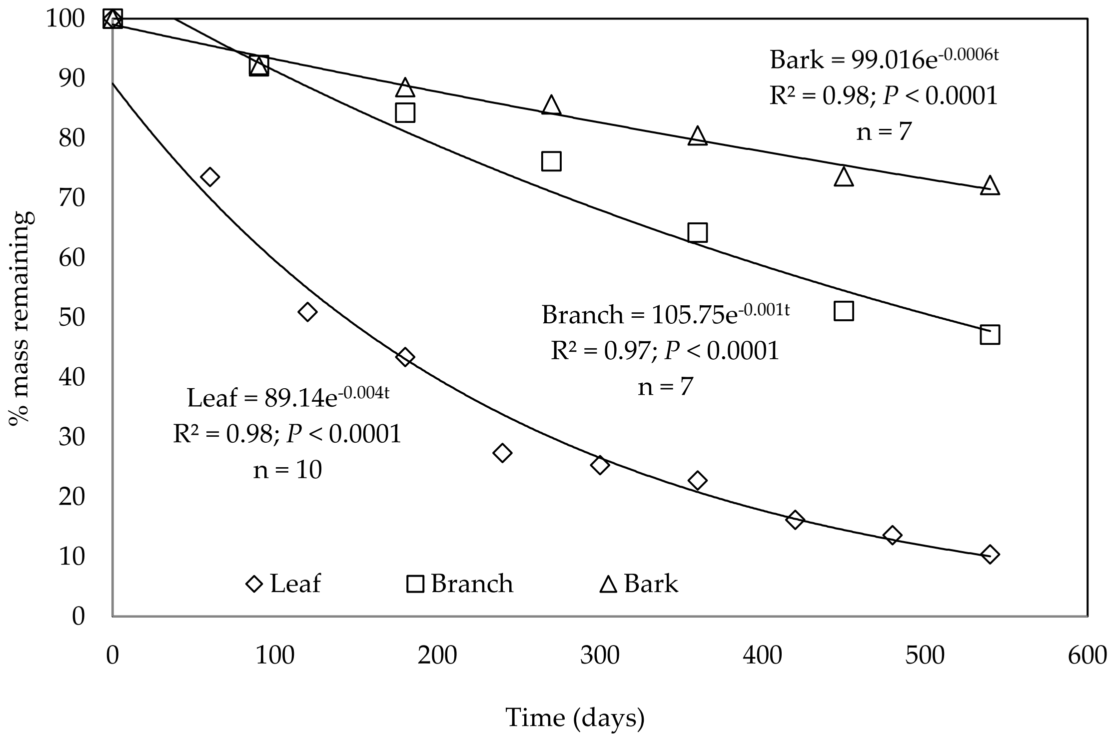

Figure 3.2. Exponential decay functions fitted to dry weight loss of harvest residue components of *A. mangium* in northern Vietnam during decomposition for 540 days.

Table 3.3. Loss of dry weight (%) over the 540-day period, decomposition constant (k, year^{-1}), the proportion of explained variation (R^2) and root mean squared error (*RMSE*) and half-life ($t_{0.5}$, year) of harvest residue components of *A. mangium* in northern Vietnam. n = 10 collection times for leaves and 7 for branches and bark.

Component	Dry weight loss (%)	k (year^{-1})	R^2	*RMSE*	$P_{\_value}$	$t_{0.5}$ (year)
Leaves	90	1.47	0.98	0.10	<0.0001	0.47
Branches	53	0.54	0.97	0.05	<0.0001	1.29
Bark	28	0.22	0.98	0.02	<0.0001	3.09

3.3. Nutrient Release During Decomposition of Harvest Residues

Among the harvest residue components, leaves consistently contained the highest concentration of N, P, K and Mg but not Ca during decomposition (Fig. 3.3). Leaves also showed the fastest release of nutrients (Fig. 3.4) as described by the single exponential model (see Supplementary Table 3.S1).

N release from decomposing harvest residue components was similar to their dry weight loss over time (Fig. 3.4), as their N concentration remained relatively stable during the study period (Fig. 3.3a). In contrast, K and Ca release from all residue components was more rapid and Mg and P release less rapid than the dry weight loss (Fig. 3.4).

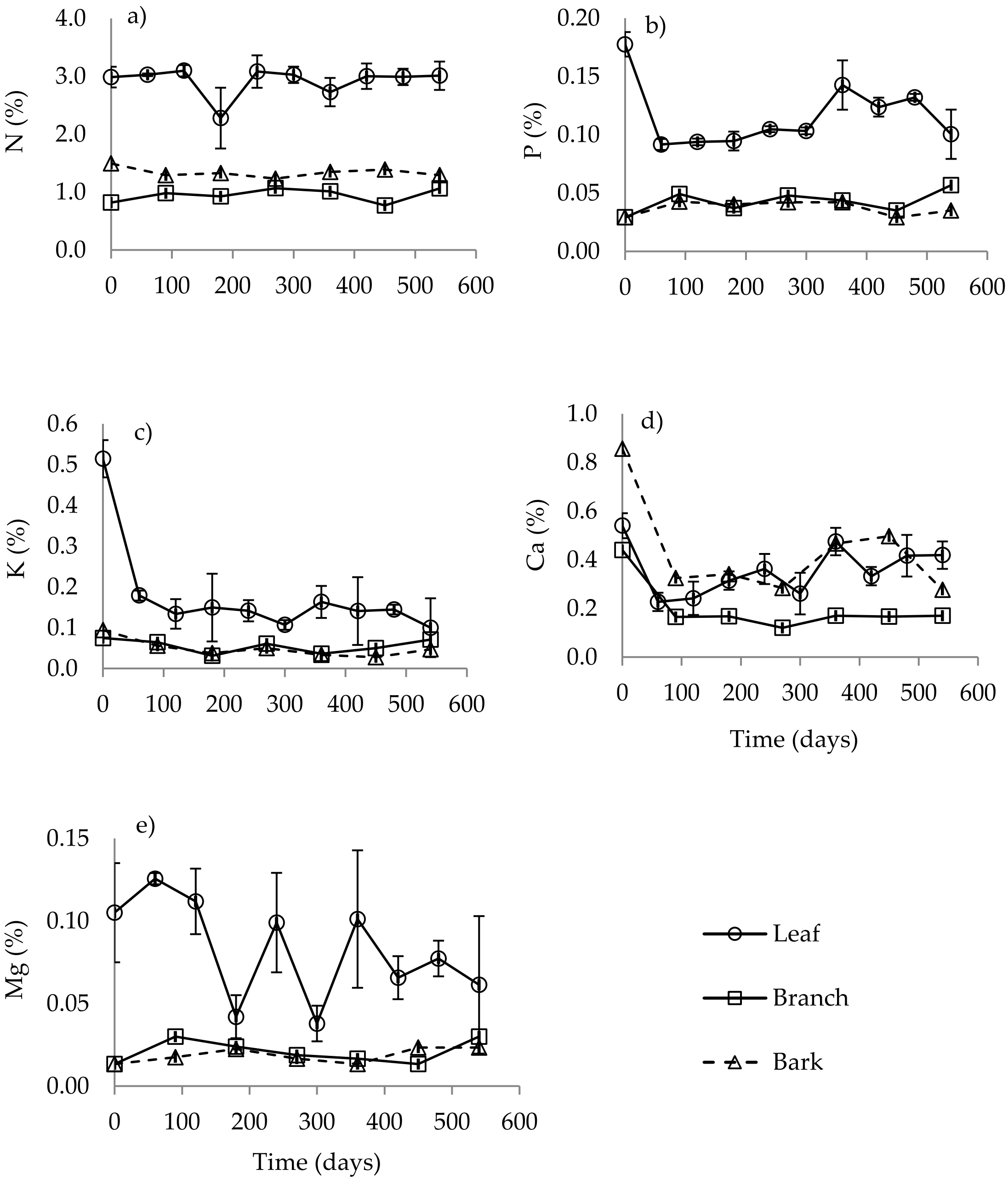

Figure 3.3. Dynamics of (a) nitrogen, (b) phosphorus, (c) potassium, (d) calcium and (e) magnesium concentration in harvest residues of *A. mangium* during the 540-day period of decomposition in northern Vietnam. Vertical bars indicate standard errors for each sampling, $n = 5$.

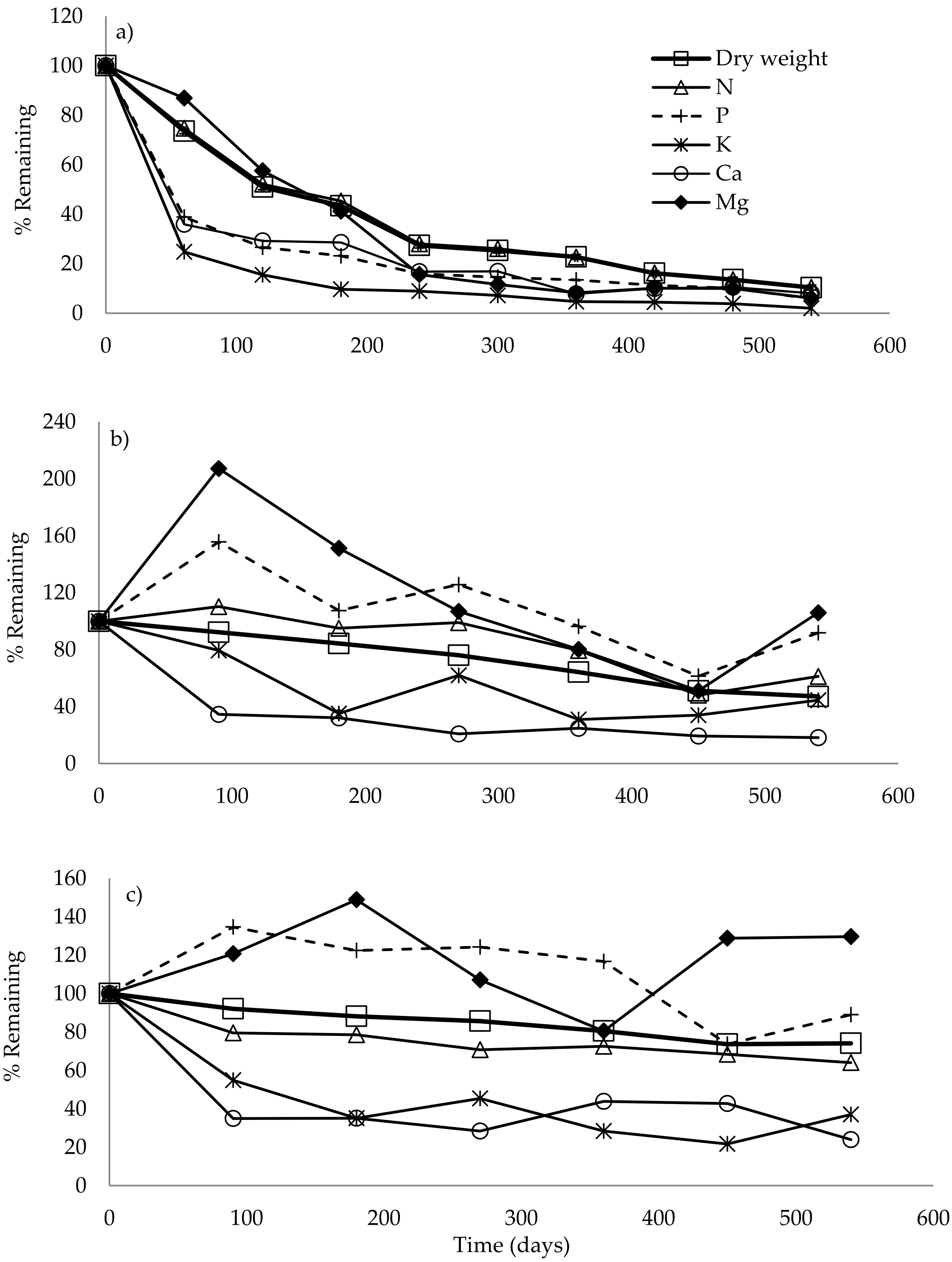

Figure 3.4. Loss of dry weight and release of nutrients during decomposition for 540 days for (a) leaves; (b) branches; and (c) bark of *A. mangium* in northern Vietnam.

Throughout the study period, the loss of Ca in all the residue components was rapid; 92%, 82% and 76% was lost in leaves, branches and bark, respectively (Fig. 3.4). The losses of K were of similar magnitude to that of Ca with 98%, 56% and 63% being lost in leaves, branches and bark, respectively (Fig. 3.4). In contrast, there was an accumulation of P and Mg, particularly in the bark and branches; P and Mg in branches were 55% and 107% higher, respectively, than their initial content 90 days after establishment (Fig. 3.4b, c).

For all components together, the amount of N, P, K, Ca and Mg that potentially could be recycled from harvest residues to the soil 18 months following logging was 137.1, 4.7, 20.8, 94.5 and 2.2 kg ha^{-1}, respectively (Table 3.4). Most of N, P, K and Mg, respectively 50%, 91%, 62% and 118% was released from decomposing leaves. The value for Mg was > 100% because the other components immobilized Mg over the first 18 months. Bark could potentially contribute 61% of the Ca, 35% of N and 25% of K (Table 3.4).

Table 3.4 Dry weight loss and nutrient release from different components of decomposing harvest residues 18 months following logging of a 7-year-old *A. mangium* plantation in northern Vietnam. Standard errors are shown in parentheses (n = 5). DM is dry matter.

Components	**Dry weight loss (t DM ha^{-1})**	**Nutrient release from decomposing harvest residues (kg ha^{-1})**				
		N	**P**	**K**	**Ca**	**Mg**
Leaves	2.3 (0.1)	68.1 (2.0)	4.3 (0.1)	12.8 (0.1)	12.6 (0.4)	2.6 (0.1)
Branches	3.5 (0.3)	20.9 (1.5)	0.2 (0.8)	2.7 (0.1)	23.7 (2.0)	−0.1 (0.0)
Bark	2.3 (0.1)	48.0 (2.8)	0.3 (0.0)	5.3 (0.2)	58.2 (1.5)	−0.4 (0.0)
Total residue with bark	8.1 (0.0)	137.1 (3.1)	4.7 (0.4)	20.8 (0.5)	94.5 (0.6)	2.2 (0.2)
Total residue without bark	5.8 (0.1)	89.0 (2.3)	4.4 (0.4)	15.6 (0.5)	36.3 (0.8)	2.6 (0.2)

3.4. Discussion

This study has shown that harvest residues retained on site in the form of bark, branches and leaves of a 7-year-old *A. mangium* plantation accounted for two-thirds of the total initial dry weight and 24%–64% of macro-nutrient contents of total residues that included litter and understorey vegetation. The export of bark from the site would lead to the significant loss of some nutrients. Decomposition rates and nutrient release from the harvest residues were associated with the nutrient concentration (substrate quality) of each residue component. Despite the limited number of mesh bags used, this study clearly demonstrated large amounts of N, K and Ca, but not P and Mg being released to the soil over the 1.5 year-study period. These results are now discussed in the context of the contribution of harvest residues to nutrient cycling in short-rotation plantations of acacia in the tropics, especially the role of bark residue.

Although the bark of the *A. mangium* represented just 15% of the total stand AGB, its export from the site would have reduced the total dry weight of all residues by one-third. The contribution of bark residue to this total dry weight was 41%, 31%, and 19% higher than that observed in *A. mangium* in Sumatra (Hardiyanto and Nambiar 2014), *A. auriculiformis* in southern Vietnam (Huong et al. 2015) and *E. dunnii* in Uruguay (Hernández et al. 2009), respectively. Potentially the contribution of bark to total stand AGB in this study and at other sites in Vietnam (also 15%) (Hai et al. 2009b) was proportionately higher than that observed in *A. mangium* in Sumatra (10%) (Hardiyanto and Nambiar 2014, Siregar et al. 2008), *A. auriculiformis* and its hybrid (*A. mangium* × *A. auriculiformis*) in Vietnam (7%–8%) (Hai et al. 2010, Huong et al. 2015) and *E. dunnii* in Uruguay (12%) (Hernández et al. 2009). For eucalypt and pine plantations, bark biomass generally accounts for 7%–10% of total stand AGB (du Toit et al. 2004, Li et al.

2011, Santana et al. 2000). Thus, retention of bark on site for *A. mangium* plantations tends to be more important in residue retention than for other species.

The bark component potentially conserved 30% of N, 18% of P, 14% of K, 41% of Ca and 6% of the Mg content of all residues for recycling. For N, this was similar to that in *A. auriculiformis* in southern Vietnam (Huong et al. 2015), but 20% and 50% greater than that in *A. mangium* in Indonesia (Hardiyanto and Nambiar 2014, Hernández et al. 2009) and *E. dunnii* in Uruguay (Hardiyanto and Nambiar 2014, Hernández et al. 2009), a difference that is attributable to the higher concentration of N in bark in the Vietnamese (1.5%) than Indonesian (1.1%) and Uruguayan (0.2%) studies. In contrast, K was between 22% and 56% lower than in these other studies (Hardiyanto and Nambiar 2014, Hernández et al. 2009, Huong et al. 2015) owing to its lower concentration (0.1% *vs*. 0.2%–0.5%). This lower concentration may be associated with soil K being less available in this study than at the other acacia sites (Hardiyanto and Nambiar 2014, Huong et al. 2015). Concentration was also the factor that led to the nutrient content of only N (30%) and Ca (41%) approximately matching bark's one-third contribution to the dry weight of all residues. Hence, retention of the bark of *A. mangium* on site at harvesting conserves some nutrients better than others and was a relatively poor source of P, K and Mg.

The patterns of mass loss during decomposition varied among components, with leaves decaying the fastest, consistent with previous reports for hardwood plantation species (Hernández et al. 2009, O'Connell 1997, Palviainen et al. 2004, Rocha et al. 2016b, Shammas et al. 2003). Among nutrients in decomposing material, the concentration of N is the most important factor determining the rate of decomposition in a given environment (Ge et al. 2013, Krishna and Mohan 2017). In this study, the decay constant (k) for leaves was 2.7 and 6.7 times higher and the N concentration 2.0 and 3.7

times higher than for branches and bark, respectively. The *k* of leaves and bark in this study were 50%–65% and 20%–50% faster, respectively, than those observed in other studies of *Eucalyptus* plantations in Australia and Uruguay (O'Connell 1997); similarly, the *k* for branches was approximately 60% faster than for *Eucalyptus* species (Hernández et al. 2009, Shammas et al. 2003), and 66%–96% faster than that observed for *Pinus radiate* D. Don plantations across New Zealand (Garrett et al. 2010). These higher *k* values are partly attributable to the higher N concentration in *A. mangium* harvest residues. In addition, higher temperatures and moisture contents in the tropical climate of Vietnam are factors that will cause faster rates of decomposition (Parton et al. 2007, Song et al. 2012, Zhang and Wang 2015). Thus, harvest residues from tropical acacia plantations release nutrients, especially N, more rapidly than other species.

During the first year of the study, net release of N was found from leaves and bark, while net immobilisation of N occurred in branches. Net N release is influenced by the C/N ratio of the decomposing materials (Ge et al. 2013, Heal et al. 1997, Hernández et al. 2009, Krishna and Mohan 2017, Moore et al. 2011, Stevenson and Cole 1999). If C/N is > 40, the net effect is N immobilization during decomposition (Parton et al. 2007). In this study, the C/N ratio of branch residue was 65 (Hai et al. 2009b), therefore the initial immobilization of its N was expected. N was subsequently mobilized owing to the oxidisation of C and N uptake, resulting in reduction of the C/N ratio during the decomposition process. Conversely, the C/N ratio of the leaf material was initially 17 and that for bark was 35 (Hai et al. 2009b). By comparison, in *E. dunnii*, the C/N ratios of leaf, branch and bark were much higher at 36, 134 and 174, respectively (Hernández et al. 2009) due to 13%−47% lower N concentration in the eucalypt harvest residues. These lower C/N ratios in acacias than eucalypts were associated with a much faster release of

N from *A. mangium* than *E.* hybrid (*E. urophylla* × *E. grandis*) harvest residues (Tchichelle et al. 2017) and higher rates of N turnover in topsoil under *A. mangium* than *E. grandis* (Voigtlaender et al. 2012). By the end of the 1.5 year study period, the total amount of N released from decomposing *A. mangium* harvest residues was 137 kg ha^{-1}, 35% of which was released from bark. In contrast, bark made no net contribution to the release of N from harvest residues of *E. dunnii* and *E. globulus* for up to two years (Hernández et al. 2009, Shammas et al. 2003) and *E. grandis*, *E. globulus*, *E. dunnii* and *Pinus taeda* for up to 6 months following harvest (Sánchez et al. 2018). While the quantities of N taken up by *A. mangium* can be as much as 180 kg ha^{-1} yr^{-1} in the first two years of growth (Hardiyanto and Nambiar 2014), *A. mangium* bark residue can potentially make an important contribution to this demand.

Over the 1.5 years of this study, harvest residues released only around 5 kg ha^{-1} of P. Other studies have found that a small amount of P at planting is sufficient to optimise growth of tropical plantation acacias (Harwood et al. 2017, Mendham et al. 2017), but this is in concentrated form near the seedling at planting, so the timing and rates of release of P from residues and its spatial distribution may not meet all of the demand for P early in the growth cycle. However, as the relative importance of the growth response to P declines with increasing stand age (Hardiyanto and Nambiar 2014, Mendham et al. 2017), the amount of P released from residues together with its release from other sources in the soil is likely to meet the demand later in the rotation.

High levels of immobilisation of P but not N in the branches and bark during decomposition suggest that P was the more limiting to microbial decomposer activity of organic matter in this system. Addition of P fertiliser has been shown to increase microbial activity in *A. mangium* plantations (Mori et al. 2013, Mori et al. 2016). Tropical plantation soils are characteristically low in soil P because of their high P-fixing capacity (Hardiyanto and Nambiar 2014, Nambiar and Brown 1997, Sam and Binh 2001) and in this study, P in the topsoil (4.0 mg kg^{-1}) was very low, even for tropical plantation soils (Tiarks and Ranger). There was also a notable decline in soil available P in this study (Bich et al. 2019a), that has also been found elsewhere in acacia plantations. Hence the addition of P fertiliser may serve an added purpose, i.e. the promotion of decomposition and nutrient release from acacia harvest residues.

The release of K and Ca was very rapid, especially during the first three months of decomposition, and reflected the high K and Ca concentrations in the harvest residues. Such rapid release of K is commonly found in plantations across a range of environments (Hernández et al. 2009, Rocha et al. 2016b, Sánchez et al. 2018, Shammas et al. 2003) because K is highly mobile; hence its rapid leaching by rain soon after placement of the mesh bags in a number of related experiments (Hernández et al. 2009, Osono and Takeda 2004, Ranjbar and Jalali 2012, Shammas et al. 2003). The rapid release of Ca and decline in Ca concentration in harvest residues is linked to the rapid release rates of Ca oxalate (Dauer and Perakis 2014, O'Connell et al. 1983) which accounts for 20%–56% of total Ca in fresh plant tissues (Dauer and Perakis 2014). Over the study period, 20.8 and 94.5 kg ha^{-1} of K and Ca, respectively, were released from the residues, with bark contributing 25% of the K and 61% of the Ca, or potentially at least one-quarter and >50% of the demand (Hardiyanto and Nambiar 2014). As growth responses to Ca and K fertilisers are uncommon in tropical acacia plantations grown with residue retention (Hardiyanto and Wicaksono 2008, Huong et al. 2015), the substantial contribution of residues to the K and Ca nutrient pools, the latter through bark, may explain this lack of response.

In contrast, the release of Mg was very slow, with net immobilisation over the first few months, especially in the branch and bark components. The slow release of Mg is because it is dependent on cellular degradation in the residues (Hernández et al. 2009, O´Connell and Grove 1996). In Ivory Coast, only 10% of initial Mg was released from decomposing litter of *A. mangium* and *A. auriculiformis* in a one-year study period (Ngoran et al. 2006). In this study, < 3 kg ha^{-1} was released, suggesting that *A. mangium* harvest residues may not meet the potential demand for Mg uptake by this species, which can be as much as 9 kg ha^{-1} year^{-1} over a similar period for an equivalent MAI (Hardiyanto and Nambiar 2014).

3.5. Conclusions

Harvest residues played a crucial role in conserving nutrients for recycling in this *A. mangium* plantation, contributing 66% of the total dry biomass and 24–64% of macronutrients, of all residues, including litter and understorey vegetation. Bark removal would have reduced the quantity of all residues by one-third, and a similar proportion of the Ca and N contents. Based on the amounts of nutrients recycled in 1.5 years of the study, we suggest that recycling of N, Ca and K, but not P and Mg, were potentially able to meet a significant part of the nutrient demand in the next rotation. While slow release should have promoted capture of the nutrients by growing trees in the next rotation, the immobilization of some nutrients such as Mg and P may limit early growth of planting trees in the first growing season. In addition, the amount of N and K lost by leaching and P to the high-fixing tropical soil remains unknown. Furthermore, a high quantity of N, but not P, released may have caused a nutrient imbalance in the soils. As P supply is crucial to the growth of these acacias, the addition of P fertiliser at planting is recommended, both to boost immediate supply and to potentially enhance decomposition rates of the harvest residues.

Supplementary materials

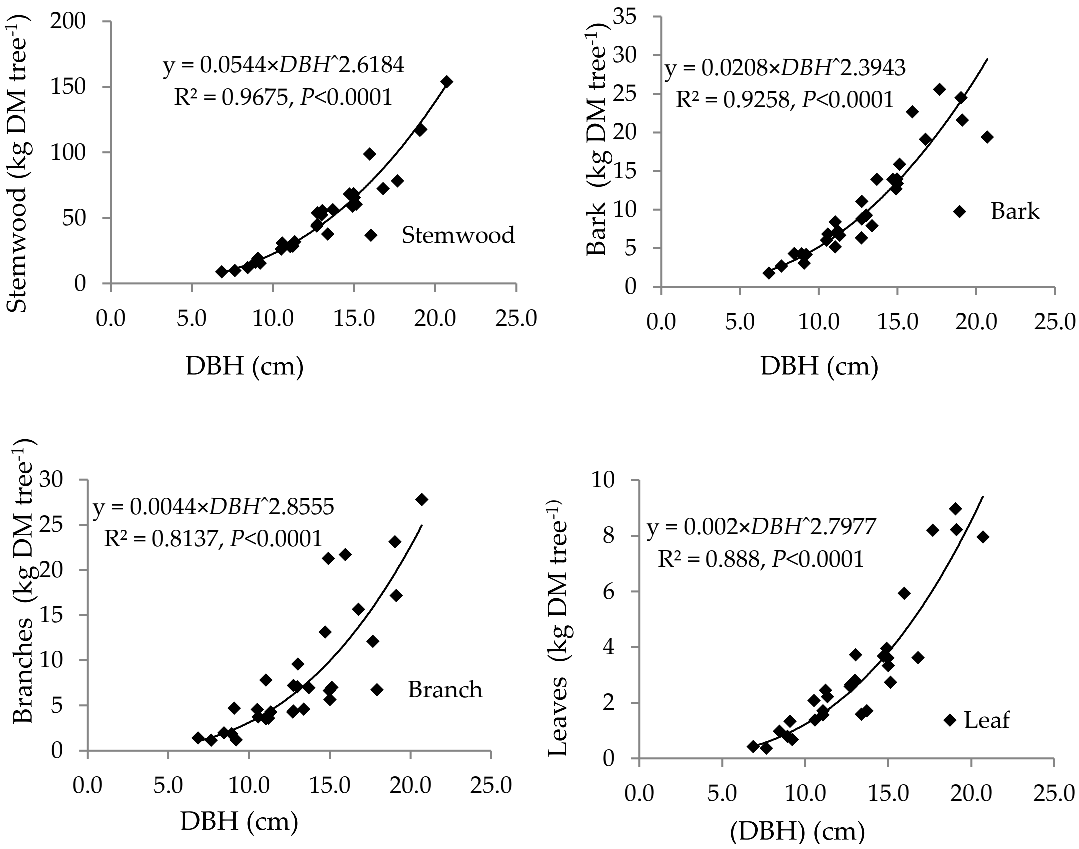

Figure 3.S1. The allometric relationships between dry biomass of stand components and tree diameter (DBH, cm). DM is dry matter. $N = 30$.

Table 3.S1. Nutrient release (%) from the leaf component over the 540-day period, nutrient release constant (k, year^{-1}), the proportion of explained variation (R^2) and root mean squared error (*RMSE*) and half-life ($t_{0.5}$, year) of nutrient degradation of *A. mangium* harvest residues in northern Vietnam. N = 10 collection times.

Elements	Nutrient release (%)	k (year^{-1})	R^2	*RMSE*	$P_{\_value}$	$t_{0.5}$ (year)
N	90	1.48	0.99	0.09	<0.0001	0.47
P	94	1.51	0.89	0.28	<0.0001	0.46
K	98	2.09	0.88	0.40	<0.0001	0.33
Ca	92	1.49	0.86	0.33	<0.0001	0.47
Mg	94	1.99	0.90	0.35	<0.0001	0.35

CHAPTER 4

EFFECT OF RESIDUE MANAGEMENT AND FERTILISER APPLICATION ON THE PRODUCTIVITY OF A *EUCALYPTUS* HYBRID AND *ACACIA MANGIUM* PLANTED ON SLOPING TERRAIN IN NORTHERN VIETNAM

Article reference:

Bich, N.V., Mendham, D., Evans, K.J., Dong, T.L., Hai, V.D., Thanh, H.V., Mohammed, C. Effect of residue management and fertiliser application on the productivity of a *Eucalyptus* hybrid and *Acacia mangium* planted on sloping terrian in northern Vietnam. *Southern Forests*, *in press*.

CHAPTER 4. EFFECT OF RESIDUE MANAGEMENT AND FERTILISER APPLICATION ON THE PRODUCTIVITY OF A *EUCALYPTUS* HYBRID AND *ACACIA MANGIUM* PLANTED ON SLOPING TERRIAN IN NORTHERN VIETNAM

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This chapter was published online in Southern Forests – a Journal of Forest Science

Abstract

Forest plantation growers in Vietnam commonly burn residues after harvesting and often apply sub-optimal amounts of nutrients during plantation establishment. We examined whether the retention of forest residue, and application of phosphorus fertiliser at higher rates compared to current practice, can increase rates of growth. A factorial combination of residue management (burning *vs*. retention) and phosphorus (P) fertiliser application at planting (15 *vs*. 100 kg ha^{-1}) treatments were applied at a steeply sloping site in North Vietnam. Two adjacent experiments were established, one with *Acacia mangium* and the other with a *Eucalyptus* hybrid (*Eucalyptus urophylla* × *Eucalyptus pellita*). Standing volume (V) and leaf area index (LAI) in *A. mangium* were greater following burning; this was mostly attributable to the significantly higher survival rate of seedlings. Burning of residues was associated with increases in the number of large branches per tree, and a higher crown damage index (CDI). In the *Eucaluptus* hybrid, diameter and height responses to the higher rate of fertilizer were observed at age 6 and 12 months, but not beyond. High P application also led to higher CDI. Standard fertiliser treatment, applied in amounts equivalent to 17, 15 and 8 kg ha^{-1} of N, P, K, respectively, was adequate to meet the early growth requirement of eucalypt and acacia plantations at this site. The relatively low amounts of harvest residue and high fertility levels at the site may have masked more significant responses of trees to the silvicultural treatments applied in this study. On steep slopes, especially if soil is poorly fertile, harvest residue retention with adequate weed and termite control may be preferential to burning as it is closely correlated with reducing factors which negatively impact productivity i.e. water run-off and soil erosion.

Keywords: burning harvest residue, phosphorus application, tropical plantation, branch size, crown damage index, slope position

4.1. Introduction

Plantation forestry makes a crucial contribution to the economy of rural areas in Vietnam through the provision of export wood-chips, and timber for a growing domestic furniture industry (Nambiar et al. 2015). By 2013 and since the 1990s, approximately 3.4 M ha of mainly acacia and eucalypt plantations had been established (MARD 2014). They are managed on 5-to-8-year rotations, and many are located on sites with steep slopes (Cao and Son 2014, Sam and Binh 2001). The current inter-rotational practices involve repeated burning of residues and litter after harvesting with application of only low amounts of organic and/or inorganic nutrients at planting (Dung et al. 2012, Nambiar et al. 2015). There is a concern that soil fertility (Dong et al. 2014, Hung et al. 2017, Huong et al. 2015) and yields (Cao and Son 2014, Dung et al. 2005, Khiet 2014) have been declining and that current residue management practices will not be able to sustain potential yield (Dung et al. 2012, Dung et al. 2005, Huong et al. 2015, Nambiar et al. 2015). In addition, damage from insect pests and diseases is further reducing yields (Ngoc et al. 2011, Thu et al. 2012).

Mismanagement site resources during the inter-rotational phase in a short-rotation silvicultural system can impact negatively on future productivity (Goncalves et al. 2013). "Slash and burn" cultivation in which the forest is clear cut, the wood removed and any remaining vegetation burnt is a traditional method of site preparation that is still used in plantation forestry in some countries, including Vietnam (Tran et al. 2011). This practice has been reported to have negative effects on the growth of eucalypts (Deleporte et al. 2008, Rocha et al. 2016a), and the tree form of acacias (Eldoma et al. 2015). Burning of residues have been linked to the loss of up to 86% of N and 60% of P in smoke and through volatilisation, and the loss of P, K and Ca through leaching, wind-blown ash, surface run-off and erosion (Gonçalves et al. 2007). Further, nutrient losses have been shown to be greater on exposed sites and those with steep slopes (De et al. 2008, Edeso et al. 1999, Sidle et al. 2006). Fast-growing short-rotation plantation acacias and eucalypts require a large nutrient supply, especially of N, P and K, at planting (Melo et al. 2016, Mendham et al. 2017); burning on steeply sloping sites therefore has the potential to reduce this supply.

In contrast, retention of harvest residues has been shown to lead to increased growth of *A. mangium* in Indonesia (Hardiyanto and Nambiar 2014), *Eucalyptus grandis* in Brazil (Rocha et al. 2016a) and *Eucalyptus globulus* in Australia (Mendham et al. 2008). The increase tree in growth has been associated with the retention of nutrients (Huong et al. 2015), enhanced soil microbial activity (Mendham et al. 2002), and increased nutrient mineralization (Nzila et al. 2002a, O'Connell et al. 2004). On steep slopes, retention of residues from harvesting can also reduce water run-off and soil erosion (Costantini and Lcoh 2002, Edeso et al. 1999, Khan et al. 2016).

Supplying nutrients as fertilizer at planting is a common practice in short-rotation forestry, and often improves productivity on nutrient deficient sites (Melo et al. 2016, Mendham et al. 2017, Xu et al. 2001). Eucalypt plantations have been shown to respond to both N and P applied at planting (Judd et al. 1996, Melo et al. 2016, Xu et al. 2001) and acacias to P applied at planting (Beadle et al. 2013, Huong et al. 2015, Mendham et al. 2017). However, responses can vary across sites depending on soil fertility and tree requirements (Mendham et al. 2017, Sankaran et al. 2007). As acacias are N-fixing, they are generally considered to have an increased requirement for P compared to non-leguminous species (Ingestad 1980). However, responses to high rates of P at planting have also been found in eucalypt plantations (Judd et al. 1996), especially in soils with low levels of extractable P (Melo et al. 2016, Xu et al. 2001). Thus high rates of P may need to be applied at planting of both acacia and eucalypt plantations to maintain and improve productivity, especially in northern Vietnam where most soils have low levels of extractable P that are considered to limit growth (Sam and Binh 2001).

On steep slopes, forest plantation productivity has also been shown to be influenced by slope position (Omary 2011, Qingshan et al. 1998). For example, in central Vietnam, Harwood et al. (2017) found that stem volume of *Acacia* hybrid (*Acacia mangium* × *A. auriculiformis*), under moderate slope, was significantly lower at the top than in the middle and bottom of the hill. This was attributable to differences in soil moisture, nutrient status and topsoil quality (De et al. 2008, Hardie et al. 2018) as well as incident solar radiation (Auslander et al. 2003) between slope positions. Hence, understanding the impact of slope and its position on tree growth could provide useful information for sustaining productivity of acacia and eucalypt plantations managed on steep slopes.

The productivity of eucalypt and acacia plantations worldwide is also increasingly threatened by insect pests and pathogens (Crous et al. 2017, Wingfield et al. 2015). Growth rates of *Acacia mangium* have been reduced from 23.5 to less than 15 m^3 ha^{-1} yr^{-1} as a result of fungal diseases (*Ganoderma philippii* and *Ceratocystis manginecans*) in Sumatra, Indonesia (Harwood and Nambiar 2014). Among the most serious pests of eucalypts in Asia is the gall wasp *Leptocybe invasa* (Dell et al. 2012, Thu 2016, Tong et al. 2016), which caused a 20% reduction in productivity of eucalypts (*E. tereticornis*, *E. camaldulensis* and *E. saligna*) in Tanzania (Kurganova et al. 2018). In Brazil, volumetric growth of *Eucalyptus urophylla* and its hybrid (*E. urophylla* × *E. grandis*) has been found to reduce up to 82% after 30 months infected by *Ralstonia solanacearum* (Ferreira et al. 2018). Tropical acacias and eucalypts are also affected by termites (Calderon and Constantino 2007, Ngoc et al. 2011), with up to 30% of infested seedlings being reported in many young acacia and eucalypt plantations across Vietnam (Ngoc et al. 2011). However, there has been limited studies linking plantation health to silvicultural practices (Jactel et al. 2009). In Australia, Pinkard et al. (2006) found that fertiliser application as N or N + P can improved crown health and productivity of a three-year-old *E. globulus* plantation which suffered from the Eucalypt weevil (*Gonipterus scutellatus*). Residue management has been found to influence community structure of invertebrate pests in wattle (*Acacia mearnsii*) plantations in South Africa with a greater infestation of soil invertebrate pests on sites where the plantation residue was windrowed–burnt–weeded or 'broadcast' (20.34%) than in the other treatments (windrowed–burnt–ripped or fallow; 2.36%) (Govender 2014). Hence, effect of silvicultural treatments to be trialled on potential biotic damage should be taken into account in any experimental design.

This paper examines whether residue retention and higher levels of P fertiliser application at planting can be used to arrest any yield decline on a steeply sloping sites and provide a pathway for sustaining higher yields in acacias and eucalypts planted in Vietnam in the longer term. We examine the effects of burning harvest residues (current practice) compared to residue retention, and the interactions between harvest residue management and P fertilizer application (current practice *vs*. a higher rate) on the productivity of *Acacia mangium* and a *Eucalyptus* hybrid (*Eucalyptus urophylla* × *Eucalyptus pellita*).

4.2. Materials and methods

4.2.1. Study site

The study site was located 170 km north of Hanoi at latitude 21°51'N, longitude 105°00'E, and altitude 100 m in a commercial forest area in Yen Bai province, Vietnam. The mean annual temperature is 22.9℃, relative humidity is commonly >75% and mean annual rainfall is 1808 mm (range 1396 - 2140 mm), most falling between May to September (Fig. 4.1).

The site had slopes ranging from 5° - 10° (at the top of the hill) to 25° - 30° (in the middle) and 30 - 40° (at the bottom). The soils at the site are classified as ferric (Ferralic) Acrisols (FAO/UNESCO/ISRIC 1988) and had mean soil pH (1:5 water) of 3.8 and Bray II extractable P of 3.5 mg kg^{-1} (Table 4.1).

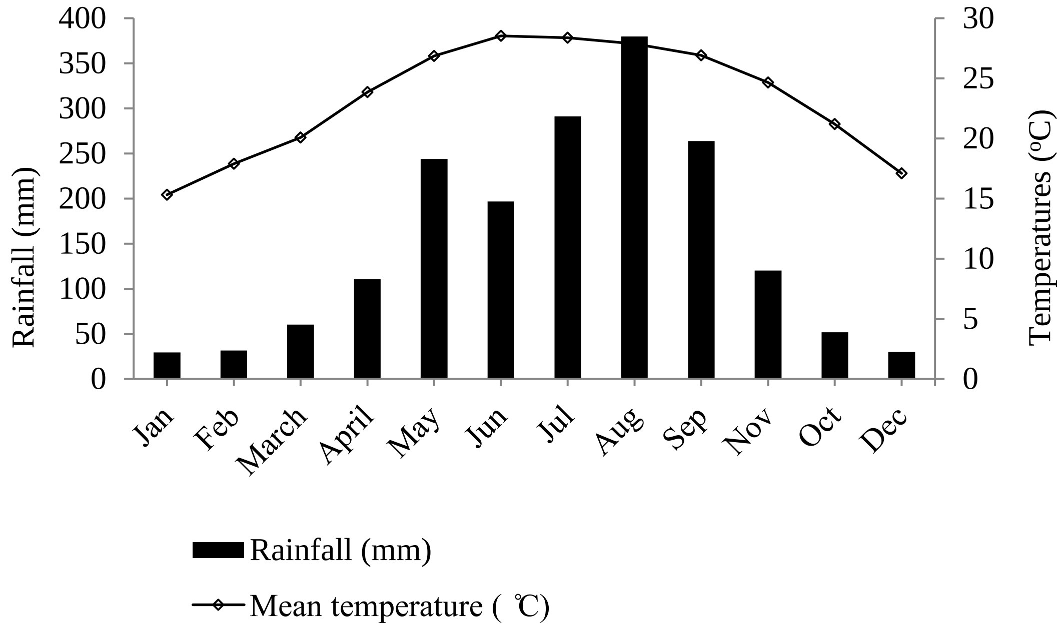

Figure 4.1. Mean monthly temperatures (*continuous line*) and rainfall (*vertical bars*) during the experimental period (2015-2017) at Yen Bai Meteorological Station in northern Vietnam.

Table 4.1. Soil chemical properties in 0-10 cm soil depth sampled immediately before establishment of the *Eucalyptus* hybrid and *Acacia mangium* trials in northern Vietnam. SE = standard error, n = 5. Soil sampling and analysis were based on the method presented in Hung et al. (2016).

Soil chemical properties	*Eucalyptus* hybrid		*A. mangium*	
	Mean	SE	Mean	SE
pH_{H2O} (1:5 water)	3.79	0.04	3.79	0.03
Total C (g kg^{-1})	27.51	2.70	29.10	2.60
Total N (g kg^{-1})	2.30	0.10	2.10	0.10
Total P (g kg^{-1})	0.08	0.00	0.09	0.00
Bray II extractable P (mg kg^{-1})	2.94	0.41	4.04	0.51
Exchangeable K (cmol kg^{-1})	0.10	0.01	0.12	0.01
Exchangeable Ca (cmol kg^{-1})	0.21	0.01	0.70	0.11
CEC (cmol kg^{-1})	10.83	0.63	7.81	0.74

4.2.2. Land use history, stand harvest, and site preparation

Historically, the site was converted from secondary forest (degraded natural forest) to plantation *Styrax tonkinensis* (Pierre) Craib in the 1980s, followed by two rotations of *A. mangium* planted in 2000 and 2008. Site preparation on each occasion involved the burning of post-harvest residues and at planting, the application of small amounts of inorganic fertiliser.

The previous stand of *A. mangium* was clear-felled in January 2015. The detailed measurements, analyses and descriptions of the stand were presented in (Bich et al. 2018). In brief, at harvesting the stand had a mean height of 14.5 m, stem diameter (DBH) of 13.2 cm, MAI of 13.3 m^3 ha^{-1} yr^{-1} and aboveground stand biomass of 60.8 Mg ha^{-1}. Stemwood, without bark, of commercial size (diameter > 3 cm over bark) was removed from the site. The other stand components (estimated to be 18.1 Mg ha^{-1}) including bark (8.9 Mg ha^{-1}), branches (< 3 cm in diameter, 6.6 Mg ha^{-1}), leaves (2.5 Mg ha^{-1}), and forest floor, including litter (5.8 Mg ha^{-1}) and understorey vegetation (3.3 Mg ha^{-1}) were retained on the site. The total initial nutrient contents in all residues maintained on the site were estimated to be 440, 15, 61, 185 and 20 kg ha^{-1} of N, P, K, Ca and Mg, respectively. The residue was distributed evenly prior to the imposition of treatments. The site then was planted with the *Eucalyptus* hybrid experiment in March-April 2015, and the *A. mangium* experiment in June 2015.

4.2.3. Experimental design and treatments

A randomised complete block experiment with five replications was applied to both the *A. mangium* and *Eucalyptus* hybrid experiments. Replicate blocks were located so as to account for slope effects, with the plots in each block having a similar slope range (5 – 10°, 20 – 30° and 30 – 40° at the top-, middle- and bottom position of the hill, respectively). Availability of the land area dictated that there was one replication at the top, two in the middle and two at the bottom of the hill for *Eucalyptus* hybrid, while for the *Acacia mangium* experiment, there was sufficient space for two replications at the top, two in the middle, and one at the bottom. Four treatments were imposed: a factorial combination of residue management (burning *vs*. retention) and P fertiliser application (current practice *vs*. a higher level of P fertiliser). Details of the treatment combinations are given below:

The two residue management treatments were

(3) S0: Residues burnt: harvest residues evenly distributed, and then all residues subsequently burnt 60 days after clear-cutting and two weeks before planting.

(4) S1: Residues retained: Harvest residues evenly distributed and no burning.

The plantation soils are dominated by acidic and leached acrisols with low available soil P (Hung et al. 2017, Phuong et al. 2012, Sam and Binh 2001, Sang et al. 2013) and P at planting is a critical requirement for growth (Hai et al. 2005, Son et al. 2006). A zero P treatment therefore was not applied and the two P fertiliser treatments were:

(3) P15: Current fertiliser practice: 17 kg ha^{-1} of N, 15 kg ha^{-1} of P and 8 kg ha^{-1} of K, applied as N:P:K 5:10:3 fertiliser.

(4) P100: High P fertilizer: As for P15 plus 85 kg ha^{-1} of P, applied as super-phosphate (16% P_2O_5), thus a total of 100 kg ha^{-1} of P.

(5) To reduce adsorption of P fertiliser onto soil reactive sites (Acrisols soil with high P-fixing capacity),

Total treatment area for the 40 plots (20 plots of 20 × 30 m for *Eucalyptus* hybrid, and 20 plots of 25 × 30 m for *A. mangium*) was 2.7 ha, i.e. 1.2 ha for *Eucalyptus* hybrid and 1.5 ha for *A. mangium*. The seedlings were sourced from a national seed orchard in Ba Vi established by the Forest Tree Improvement and Biotechnology Research Institute, Vietnamese Academy of Forest Sciences, Hanoi. Seedlings were planted in 30 × 30 × 30 cm planting holes with spacing between plants of 2 m × 3 m (1666 trees ha^{-1}) in the *Eucalyptus* hybrid trial, and 2.5 m × 3 m (1333 trees ha^{-1}) in the *A. mangium* trial. To reduce adsorption of P fertiliser onto soil reactive sites (Acrisols soil with high P-fixing capacity (Sam and Binh 2001)), fertiliser was applied in the base of the planting hole without mixing through the soil and covered by a soil layer before planting the trees. Weed control was applied to whole area across all treatments, using a wood-handle machete, at six monthly intervals following planting and until canopy closure (2 years following planting). The tree measurements were made on net plots (a sampling area within the treatment area) of six rows of six trees to provide plot areas of 216 m^2 and 270 m^2 in *Eucalyptus* hybrid and *A. mangium*, respectively. Each net plot was surrounded by two rows of buffer trees on all sides.

4.2.4. Experimental measurements and calculations

Tree growth

Tree size was measured at 6, 12, 18 and 24 months after planting. Diameter (DBH, cm) at breast height (1.3 m) was measured, as was total tree height, H (m). Numbers of dead trees were recorded in each plot. Stem volume (V) of *A. mangium* and *Eucalyptus* hybrid was calculated using Equations 1 and 2 (MARD 2001), respectively.

$$V = \frac{\pi}{4} \times DBH^2 \times H \times 0.490 \qquad (1)$$

where 0.490 is the stem form factor and

$$V = 0.3256 \times (DBH^2 \times H)^{0.9106} \qquad (2)$$

Standing volume was calculated as the sum of the individual stem volumes per plot, and expressed per ha.

In addition to the tree growth measurements, geographic location and slope angle of each plot were determined by GPS (Garmin 60CSx; Garmin Ltd, Olathe, KS, USA) and Abney hand level (CST/berger 5.25'' 17-640), respectively. Furthermore, three soil pits per slope position (total of 9 pits, representing three slope positions i.e. top, middle and bottom) in each species, were dug to measure soil profile and soil depth.

Leaf area index

Leaf area index (LAI) was determined at age 6, 12, 18 and 24 months after planting by using a destructive harvesting method (du Toit and Dovey 2005). Ten trees representing the range of diameter classes of each species were destructively sampled from the buffer rows of the experimental plots at each assessment time. After felling the trees, DBH and H of the trees was assessed, and fresh mass of leaves of each tree was determined in the field. A sample of 20 representative fresh leaves per tree was selected. The sample leaves were scanned with a Canon scanner (Canon Scanner Lide 210) and leaf area was determined by using LIA32 software (version V0.377e) (Yamamoto 2004). All samples were then oven dried to constant mass at 65 ° C and then weighed for conversion of fresh sample mass to oven-dry mass and calculation of specific leaf area (the ratio of leaf area to leaf dry weight, m^2 kg^{-1}) of each sample tree. Leaf area of each sample tree was determined by multiplication of the leaf dry mass and its specific leaf area. Leaf area of the destructive sample trees were regressed against the tree diameter (DBH) and height (H), and the models explaining the largest portion of the variation were used to estimate leaf area of individual trees in plots (for *Eucalyptus* hybrid: leaf area = $0.8421 \times DBH^{1.5228}$, $R^2 = 0.88$, $P < 0.001$; and for *A. mangium*: leaf area = $3.5965 \times DBH - 0.7609$, $R^2 = 0.90$, $P < 0.001$). Total leaf area per plot was calculated as the sum of the leaf area of individual trees in the plot. LAI was determined as the total leaf area of plot divided by plot area.

Tree form

Tree form was assessed at age 12 months. The number of competing leaders per tree and the number of large branches > 10 mm in diameter from the main stem (or stem with the largest diameter if not single-stemmed) were measured (Beadle et al. 2007, Medhurst et al. 2003). As the preferred form for harvesting is single stems (Beadle et al. 2007), more competing leaders or large branches per tree are associated with poorer tree form.

Crown damage index

Crown damage was assessed at age 12 months using methodology developed for young eucalypts by Stone et al. (2003).

Crowns of each tree were divided vertically into thirds based on tree height, and a separate assessment done for each third. Three types of leaf damage were assessed: defoliation (damage from chewing insects), necrosis and discoloration. Crown condition of both species was expressed as the crown damage index (CDI):

$$\mathrm{CDI} = \frac{D_s \times D_i}{100} + \frac{N_s \times N_i}{100} + \frac{C_s \times C_i}{100} \quad (3)$$

where (*D*) denotes defoliation, (*N*) denotes necrosis and (*C*) denotes foliage discoloration. The subscripts are (*i*) incidence, estimated as the percentage of leaves in the crown affected by the specified type of damage relative to the crown of an undamaged tree on that site, and (*s*) severity, estimated as the average percentage area of leaf with the specified type of damage. The CDIs for each third of the tree were summed to calculate the CDI per sampled tree.

Visual standards for *D*, *N* and *C* for *Eucalyptus* hybrid were based on Stone et al. (2003). Using on-site material, a visual standard was developed for *A. mangium* (details are given in Supplementary Fig. 4.S1) based on the range of leaf areas showing each type of damage. In both species, a time limit was not set for each evaluation, but assessors were asked to walk around the tree and assess damage looking away from the sun (Smith et al. 2005). Prior to the assessments, all assessors were trained in the method and tested for consistency in their assessments.

Foliar sampling and analysis

Foliage was sampled at ages one and two years after planting (in March 2015 and 2016 for *Eucalyptus* hybrid, and June 2015 and 2016 for *A. mangium*). Foliar sampling and analysis procedures were based on Judd et al. (1996). In brief, a single bulked sample of 40 fully expanded leaves was sampled from the outer branch position of the upper third of the crown of five dominant and co-dominant trees in the inner rows of each plot (total of 20 samples per species per collection time).

The samples were dried to a constant weight at 65℃ and then ground to pass a 2 mm mesh sieve. The ground material was redried (65℃ overnight) prior to digestion in concentrated sulphuric acid and 30% hydrogen peroxide and all nutrients were measured from that digest. Total N was analyzed by Automatic Kjeldahl distillation (UDK 149, PLT Scientific SDNBHD, Puchong Selangor Darul Ehsan, Malaysia), P by spectrophotometry (Jasco 7800 spectrophotometer-JASCO International Co., Ltd, Tokyo, Japan), K by flame photometry (Model 410 Flame Photometer Range—Sherwood Scientific Ltd, Cambridge, UK), and Ca and Mg by atomic absorption spectroscopy (Berry and Johnson 1966).

4.2.5. Statistical analysis

The effect of treatment on survival, growth (DBH, H and V), LAI, form (the number of competing leaders and the number of branches > 10 mm), CDI and foliage nutrient concentration was investigated using two-way analysis of variance (ANOVA) of two levels of P fertiliser and two types of residue management in five topographically arranged blocks. The effects of slope (which was used as a surrogate for position in the landscape) on the tree growth parameters, LAI, form and CDI were explored using regression analysis. Statistical tests were conducted with SPSS for Windows version 22.0 (IBM Corp, 2013).

4.3. Results

4.3.1. Survival

Survival of trees to age 24 months was consistently high in all treatments in the *Eucalyptus* hybrid trial (95−96%) but was variable in the *A. mangium* (82−93%) trial (Table 4.2). A lower survival rate in the *A. mangium* plots was observed when residue was retained rather than burned ($P < 0.05$, Table 4.2, also see Supplementary Table 4.S1 for summary of statistical analysis). Rate of P fertiliser application did not significantly affect survival of either *A. mangium* or *Eucalyptus* hybrid in either trial, nor did residue management in the *Eucalyptus* hybrid trial.

Regression analysis showed that slope had no significant effect on survival in either the *Eucalyptus* hybrid or *A. mangium* trial for the duration of the study period ($P > 0.10$, data not shown).

Table 4.2. Mean survival of trees (%) 6, 12, 18 and 24 months (mo) after planting according to the residue management or fertiliser treatments in an *Eucalyptus* hybrid and *A. mangium* residue management and fertilisation trial in northern Vietnam. Means within columns sharing the same letters are not significantly different at $P < 0.05$. Full analysis shown in Supplementary Table 4.S1.

Treatments		*Eucalyptus* hybrid				*A. mangium*			
		6 mo	12 mo	18 mo	24 mo	6 mo	12 mo	18 mo	24 mo
Residue management*	S0	98[a]	97[a]	97[a]	96[a]	96[a]	95[a]	93[a]	93[a]
	S1	96[a]	95[a]	95[a]	95[a]	91[b]	88[b]	83[b]	82[b]
Fertiliser application**	P15	98[a]	97[a]	96[a]	96[a]	92[a]	90[a]	86[a]	86[a]
	P100	97[a]	96[a]	96[a]	95[a]	95[a]	94[a]	89[a]	88[a]

*S0 and S1 are burning and retention of residue, respectively

** P15 is the low (15 kg ha^{-1}) and P100 the high (100 kg ha^{-1}) rate of phosphorus fertiliser

4.3.2. Growth

There was no significant interaction between residue management and rate of P fertiliser application on measures of tree growth (DBH, H and V) for either species ($P > 0.05$). Therefore, only the main effects are presented.

The standing volume (V) of *A. mangium* at age 24 months after planting was significantly higher when residue was burned than when residue was retained ($P < 0.05$, Table 4.3, supplementary Table 4.S1). Neither stem diameter (DBH) nor tree height, H, of *A. mangium* responded significantly to the residue management treatments at age 6, 12, 18 or 24 months after planting ($P > 0.05$, Table 4.3). The higher levels of competition in the residue retained treatments might have masked other growth responses to treatments if weeds were not adequately controlled. Residue management had no effect on tree growth in the *Eucalyptus* hybrid trial ($P > 0.05$, Table 4.3).

Table 4.3. Mean stem diameter (DBH), tree height (H) and standing volume (V) of *Eucalyptus* hybrid and *A. mangium* in response to residue management treatments (burning *vs.* retention) at 6, 12, 18 and 24 months (mo) after planting in northern Vietnam. Means within columns sharing the same letters within each growth attribute are not significantly different at $P < 0.05$. Full analysis shown in Supplementary Table 4.S1.

Tree growth	Treatment	*Eucalyptus* hybrid				*A. mangium*			
		6 mo	12 mo	18 mo	24 mo	6 mo	12 mo	18 mo	24 mo
Stem diameter at 1.3 m (cm)	Burning	2.9[a]	5.1[a]	6.7[a]	7.5[a]	1.4[a]	3.4[a]	6.1[a]	7.0[a]
	Retention	2.8[a]	5.1[a]	6.8[a]	7.7[a]	1.3[a]	3.2[a]	5.9[a]	6.7[a]
Tree height (m)	Burning	4.0[a]	6.7[a]	9.7[a]	10.2[a]	2.2[a]	3.5[a]	6.1[a]	6.8[a]
	Retention	4.1[a]	6.9[a]	9.9[a]	10.5[a]	2.1[a]	3.4[a]	6.0[a]	6.5[a]
Standing volume (m^3 ha^{-1})	Burning	-	5.8[a]	13.0[a]	39.5[a]	-	2.5[a]	14.4[a]	21.7[a]
	Residue	-	6.0[a]	13.4[a]	42.0[a]	-	1.8[b]	11.5[a]	17.0[b]

(-) means standing volume was not calculated at age 6 months

In the *Eucalyptus* hybrid trial, DBH and H responded significantly to the higher level of P application at ages 6 and 12 months; however, there were no significant differences between treatments at age 18 and 24 months (Table 4.4). There were no significant differences at 24 months between the fertiliser treatments as measured by DBH and H of *A. mangium* and in standing volume of either *A. mangium* or *Eucalyptus* hybrid at 24 months ($P > 0.05$, Table 4.4).

Table 4.4. Mean stem diameter (DBH), tree height (H) and standing volume (V) of *A. mangium* and *Eucalyptus* hybrid in northern Vietnam at ages 6, 12, 18 and 24 months (mo) in response to fertilizer treatments applied at planting. Means within columns sharing the same letters within each growth attribute were not significantly different at $P < 0.05$. Full analysis shown in Supplementary Table 4.S1.

Tree growth	Treatment*	*Eucalyptus* hybrid				*A. mangium*			
		6 mo	12 mo	18 mo	24 mo	6 mo	12 mo	18 mo	24 mo
Stem diameter at 1.3 m (cm)	P15	2.7^{a}	5.0^{a}	6.7^{a}	7.5^{a}	1.3^{a}	3.3^{a}	6.1^{a}	7.0^{a}
	P100	3.0^{b}	5.2^{b}	6.9^{a}	7.7^{a}	1.4^{a}	3.3^{a}	5.9^{a}	6.7^{a}
Tree height (m)	P15	3.9^{a}	6.6^{a}	9.7^{a}	10.2^{a}	2.1^{a}	3.4^{a}	6.1^{a}	6.7^{a}
	P100	4.2^{b}	7.0^{b}	9.9^{a}	10.5^{a}	2.2^{a}	3.5^{a}	6.0^{a}	6.5^{a}
Standing volume (m^3 ha^{-1})	P15	-	5.6^{a}	12.8^{a}	40.2^{a}	-	2.1^{a}	13.7^{a}	20.4^{a}
	P100	-	6.2^{a}	13.6^{a}	41.3^{a}	-	2.2^{a}	12.2^{a}	18.2^{a}

(-) means standing volume was not calculated at 6 months

*P15 and P100 are the low (15 kg ha^{-1}) and the high rate (100 kg ha^{-1}) of phosphorus fertiliser

Negative relationships between tree growth (DBH, H, and V) were observed with slope early in stand development in *A. mangium*, but disappeared with time (data not shown). There was no effect ($P > 0.05$) of slope on the growth (DBH, H and V) of *Eucalyptus* hybrid (data not shown).

4.3.3. Leaf area index

Mean values of leaf area index (LAI) at ages 6, 12, 18 and 24 months after planting for *Eucalyptus* hybrid were 1.2, 2.2, 2.3 and 2.9 m^2 m^{-2}, respectively, and for *A. mangium* 0.3, 1.4, 2.9 and 3.5 m^2 m^{-2}, respectively. There was no significant effect of residue management, or interaction between residue management and fertilizer, on LAI for *Eucalyptus* hybrid ($P > 0.05$, Fig. 4.2a), however burning resulted in a significantly increased LAI of *A. mangium* at age 12, 18 and 24 months ($P < 0.05$, Fig. 4.2b, supplementary Table 4.S1).

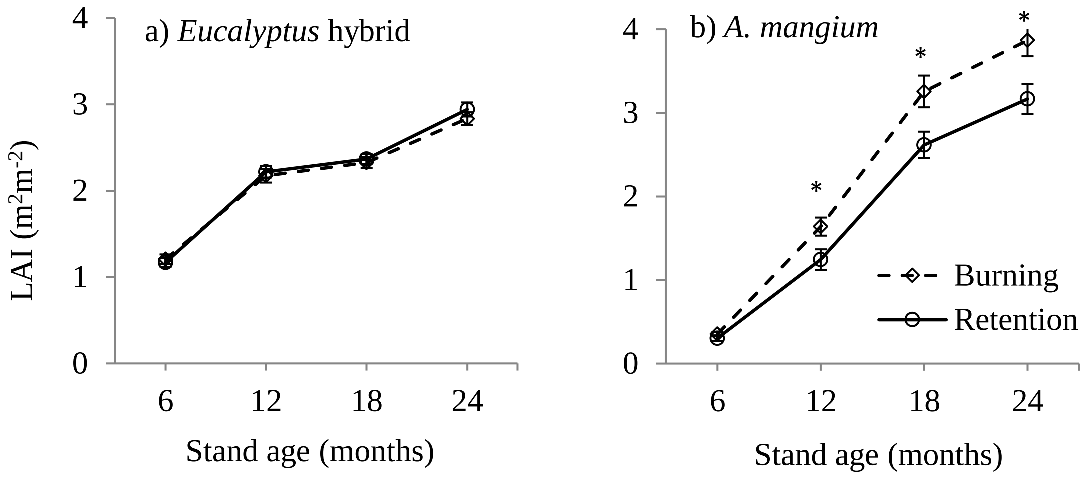

Figure 4.2. Leaf area index of *Eucalyptus* hybrid (a) and *Acacia mangium* (b) according to residue management treatments 6, 12, 18 and 24 months after planting in northern Vietnam. The asterisk denotes a statistically significant difference between treatments ($P < 0.05$). Error bars represent ± 1 standard error of the mean.

Application of 100 kg ha^{-1} of P fertiliser at planting to *Eucalyptus* hybrid resulted in a higher LAI than the lower rate at age 6 months ($P < 0.05$), but the effect was no longer significant at age 12, 18 and 24 months ($P > 0.05$, Fig. 4.3a). Application of the higher rate of P had no effect on the LAI of *A. mangium* ($P > 0.05$, Fig. 4.3b, supplementary Table 4.S1).

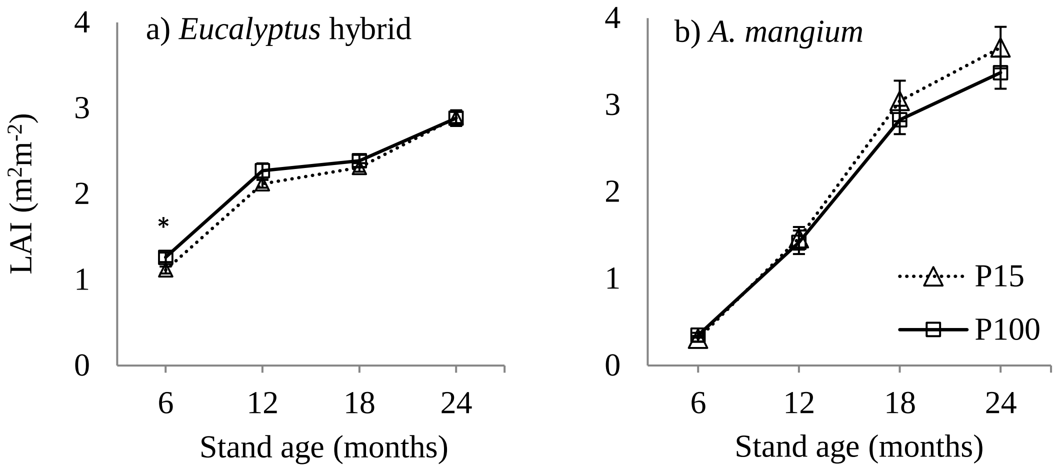

Figure 4.3. Leaf area index of *Eucalyptus* hybrid (a) and *Acacia mangium* (b) according to the amount of P fertiliser applied (P15 = 15 kg ha^{-1}, P100 = 100 kg ha^{-1}) 6, 12, 18 and 24 months after planting in northern Vietnam. The asterisk denotes a statistically significant difference between treatments ($P < 0.05$). Error bars represent ± 1 standard error of the mean.

At 24 months, there was no effect of position on the landscape on LAI of both *Eucalyptus* hybrid and *A. mangium* plantations (data not shown).

4.3.4. Form

Twelve months after planting, the percentage of the trees that had less than two large branches (> 10 mm) was 80% and 25% in the *Eucalyptus* hybrid and *A. mangium* trials, respectively. The percentage of the trees with a single leader was > 90% and > 70% in the *Eucalyptus* hybrid and *A. mangium* trials, respectively. There was no effect of residue management and fertiliser on tree form for either species ($P > 0.05$).

The residue-management treatment had no effect on either the number of large branches or competing leaders per tree for *Eucalyptus* hybrid ($P > 0.05$, data not shown). In contrast, residue management had a significant effect on the number of large branches ($P < 0.05$), but not on the number of competing leaders per tree ($P > 0.05$) for *A. mangium*, with a lower percentage of trees having less than two large branches per tree and a higher percentage of trees having ≥

eight large branches per tree when residue was burned compared to it being retained ($P < 0.05$, Fig. 4.4).

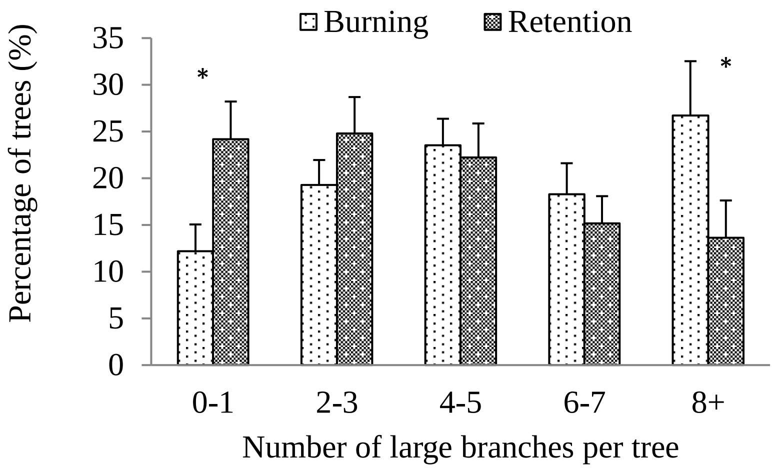

Figure 4.4. The effect of residue management treatment on the number of large branches >10 mm per tree 12 months after planting in *A. mangium* plantations in northern Vietnam. Error bars represent +1 standard error of the mean. The asterisk indicates a significant difference ($P < 0.05$).

Fertiliser treatment had no significant effect on either the number of large branches or number of competing leaders for both *A. mangium* and *Eucalyptus* hybrid at 12 months after planting ($P > 0.05$, data not shown).

Regression analysis showed that slope had no significant effect ($P > 0.05$) on the form of *Eucalyptus* hybrid (data not shown). Higher slope did significantly increase the number of large branches per tree in *A. mangium* ($P < 0.05$), but there was no effect on the number of competing leaders per tree ($P > 0.05$, data not shown).

4.3.5. Crown damage index

Mean crown damage index (CDI) at age 12 months across the treatments of both species was 5.2%. The mean score of each component of the CDI (defoliation damage from chewing insects, necrosis or discoloration) of both species was < 3%. The major contribution to the CDI of *Eucalyptus* hybrid was fungal diseases, while the CDI of *A. mangium* was mostly attributable to insect pests.

Burning residue after harvesting had no effect on CDI of *Eucalyptus* hybrid ($P > 0.05$, Fig. 4.5a), but it did significantly increase the CDI of *A. mangium* ($P < 0.05$, Fig. 4.5b). Conversely, higher fertiliser application significantly increased the CDI of *Eucalyptus* hybrid ($P < 0.05$, Fig. 4.5a), but not of *A. mangium* ($P > 0.05$, Fig. 4.5b, supplementary Table 4.S1).

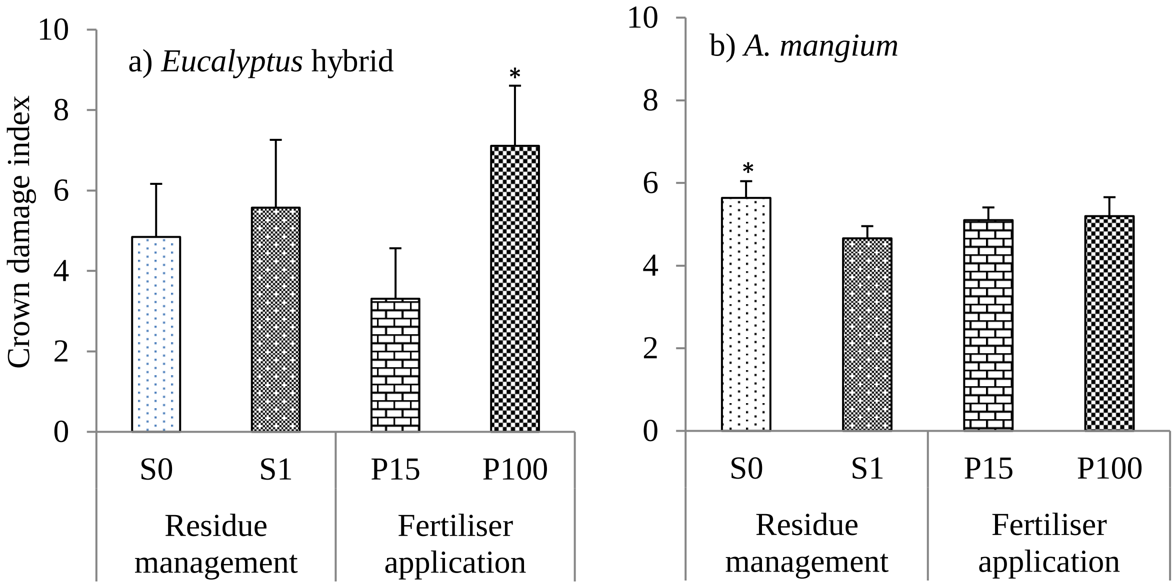

Figure 4.5. Crown damage index of *Eucalyptus* hybrid (a) and *A. mangium* (b) with residue management treatment (S0 = burning, S1 = retention) and amount of P fertiliser applied at planting (P15 = 15 kg ha^{-1}, P100 = 100 kg ha^{-1}) 12 months after planting in northern Vietnam. The asterisk indicates there was a significant main effect of treatment ($P < 0.05$). Error bars represent +1 standard error of the mean.

Regression analysis showed that higher slope significantly decreased the CDI of both species ($P < 0.001$, Fig. 4.6).

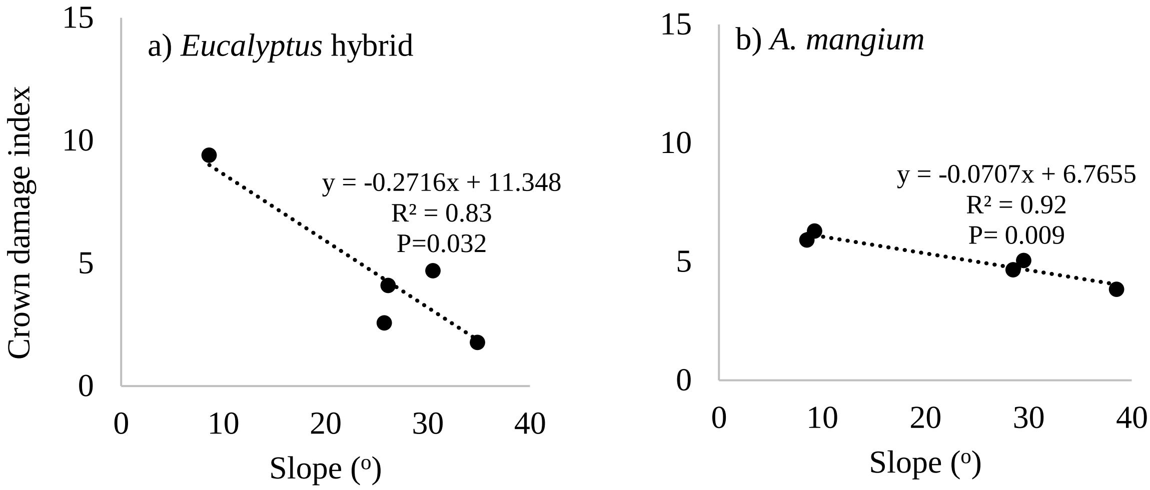

Figure 4.6. Relationship between slope within trial site and crown damage index of *Eucalyptus* hybrid (a) and *A. mangium* (b) 12 months after planting in northern Vietnam.

3.6. Foliar nutrient concentration

Harvest residue management and P fertiliser application treatments had no effect on foliar nutrient concentration of either *Eucalyptus* hybrid or *A. mangium* at ages one and two years after establishment (P > 0.05). Therefore, only the average values are presented (see Supplementary Table 4.S2).

4.4. Discussion

This study investigated the influence of high P fertiliser applied at planting and the inter-rotational practice of residue burning or retention on tree growth, LAI, form and CDI. While these silvicultural treatments have previously been explored in acacia and eucalypt forestry in South East (S-E) Asia and elsewhere, this study focused on a plantation established on a steeply sloping site that is typical of many in Vietnam and other S-E Asian countries. The results demonstrated that the current practice of applying 15 kg ha^{-1} of P (P15) was adequate to address any P deficiency in the first 2 years after planting. Residue management treatments had no effect on DBH and H of either *A. mangium* or *Eucalyptus* hybrid; however, retention of harvest residue improved tree form and crown health of acacia compared to acacia in the burning treatment.

Residue treatment had no significant effect on DBH, H, V or LAI of *Eucalyptus* hybrid at age 24 months. Burning of residues after harvesting has been shown to increase tree diameter and height in the short term because of the release of nutrients from ash and the higher rates of mineralisation (Deleporte et al. 2008, Gonçalves et al. 2008), though the growth response can be dependent on site fertility. For example, Mendham et al. (2008) found that there were no differences in the growth of *E. globulus* between treatments where residue was retained or burnt on a highly productive red earth site in south-western Australia; however on a low productivity grey sand site there was a growth response to residue retention (Mendham et al. 2008). Soil total C and N in our study ranged from 27.5 – 29.1 g kg^{-1} and 2.1 – 2.3 g kg^{-1}, respectively. These are high values for Vietnam (Dong et al. 2014, Hung et al. 2017) and at least average for a range of tropical forest soils (Tiarks and Ranger 2008). This suggests that the Yen Bai site has at least moderate inherent fertility that may have masked any increase in the nutrient supply following burning. That the standing volume of *Eucalyptus* hybrid at 24 months (39.5 – 42.0 m^3 ha^{-1}) was high for this environment in Vietnam (Nghia et al. 2010, Thinh et al. 2015), supports this assertion. The relatively low mass of residues (27 Mg ha^{-1}) compared to that in other studies in the tropics, 38-135 Mg ha^{-1} (Hardiyanto and Nambiar 2014, Huong et al. 2015) may also have been insufficient to significantly change the supply at this site. In *E. grandis* and *E. tereticornis* in India, lack of response of tree growth (DBH, H and V) to residue management treatments was due to low amount of harvest residue retained at the sites such as Punnala and Surianelli or being masked by high inherent soil fertility in Vattavada site (Sankaran et al. 2007). Thus it appears that, in the eucalypt in this study, low amount of harvest residue and high site fertility resulted in the absence of growth response to the residue management treatments.

In contrast, burning led to higher V and LAI at 24 months in *A. mangium*; V was 28% greater (21.7 *vs* 17.0 m^3 ha^{-1}) and LAI was 22% greater (3.9 *vs* 3.2 m^2 m^{-2}) than where residue was retained. However, this difference can be largely attributed to the 13% higher survival rates of trees in the burning treatment at that age. The higher rates of survival were most likely due to lower termite damage in the burnt treatment (Hoang Van Thanh pers. comm., [Vietnamese Academy of Forest Sciences][2017]).

Compared to 15 kg ha^{-1}, application of 100 kg ha^{-1} P significantly increased the DBH and H of *Eucalyptus* hybrid at ages 6 and 12 months, but this benefit disappeared at the later ages. Early growth responses of eucalypts to P fertiliser at planting can be dependent on the underlying soil P concentration (Melo et al. 2016, Xu et al. 2001). For eucalyptus hybrids (*E. grandis* × *E. urophylla* and *E. urophylla* × *E. globulus*) planted in Brazil at a site with resin-extractable soil P of 1.4 mg kg^{-1}, stand volume responded positively as P fertiliser application at planting was increased from 13 – 40 kg ha^{-1}; however, there was no response to P fertiliser when resin-extractable soil P was 8.7 mg kg^{-1} (Melo et al. 2016). At sites in China, DBH and H of *E. urophylla* and *E. globulus* also responded positively up to age 3 years to P fertiliser applied at planting; the optimum rates of application for V production at that age were 200 and 40 kg P ha^{-1}, respectively, where soil Bray I extractable P was 1.5 mg kg^{-1} and 8.7 mg kg^{-1} (Xu et al. 2001). For *E. globulus* at several sites in Australia where Bray I extractable P ranged from 7.1 to 26.7 mg kg^{-1}, applications of P up to 50 kg ha^{-1} to age 9 months led to volume gains up to age 26 months (Judd et al. 1996). In the current study, soil Bray II extractable P was 2.9 mg kg^{-1}, at the lower end of the range of P in the sites reported above, and high P also accelerated early growth. By 18 months, however, there were no longer any growth responses to the high P fertiliser at planting treatment.

Demand for P by eucalypts declines with time, a finding that is supported by a decreasing growth response to P fertiliser at later stages of stand development (Melo et al. 2016); for example, the annual demand for P in a short-rotation *E. grandis* plantation in Brazil was greatest in the first year (Leite et al. 2011). Early growth requires a high uptake of nutrients to support rapidly developing root and leaf biomass (Miller 1995). As a tree ages its root system (and associated mycorrhizae) extends and accesses increasing amounts of resident soil P (Gonçalves et al. 2004, Harrison et al. 1988, Miller 1995). Crown development leads to an increase in LAI (Smethurst et al. 2003), which results in the faster development of intraspecific competition in higher P treatments because of the greater retranslocation of P within the tree (Gonçalves et al. 2004, Miller 1995, Niederberger et al. 2017). Thus high P applied at planting can be used to stimulate more rapid early establishment and may bring forward the harvest age at some sites, but its relative effect compared to a lower application of P is likely to decline with stand age, and as with this study, it can disappear entirely.

In contrast to *Eucalyptus* hybrid, the higher level of P had no significant effect on DBH, H, V or LAI of *A. mangium*. While tropical acacias can respond to P fertiliser applied at planting, the quantity required for optimum response has generally been low (Hardiyanto and Nambiar 2014, Huong et al. 2015). Mendham et al. (2017) applied four rates of P fertiliser (0, 10, 20 and 100 kg ha^{-1}) at planting to *A. mangium* across 11 sites in South Sumatra, Indonesia. At 10 of these sites there were significant responses of V to P, and at nine, V was more than double that in the zero P-fertiliser treatment up to age 3 years. However, the quantity of P fertiliser required to achieve this level of response was generally low and it declined over time, with an average across sites of 23, 5.1 and 2.7 kg ha^{-1} of P at establishment able to provide 90% of maximum growth at ages 1, 1.5 and 3 years, respectively (Mendham et al. 2017). In some cases, the lack of a growth response to high P application may be due to induced nutrient imbalances such as N:P ratio (Güsewell 2004). In the current study, foliar concentration of N, P and N:P ratios of *A. mangium* ranged from 2.8 – 3.0%, 0.15 – 0.17% and 17 – 19, respectively, during 12 and 24 months following planting and these are within the range observed for *A. mangium* in tropical plantations (Hardiyanto et al. 2004, Majid and Paudyal 1999), suggesting that neither N nor P were limiting tree growth (Paudyal and Majid 2000). Thus the current practice of applying 15 kg P ha^{-1} in northern Vietnam (P15) should remain adequate to address any P deficiency in the first 2 years after planting.

P fertiliser and residue management treatments had no effect on the number of large branches and leaders per tree of *Eucalyptus* hybrid or the number of leaders per tree of *A. mangium*. Fertiliser application can increase branch size and/or numbers of competing leaders (Bon and Harwood 2016, Neilsen 1996, Wiseman et al. 2006). In *Eucalyptus nitens* and *E. regnans* in Australia, greater branch size and numbers of competing leaders were found on trees that received 151, 74 and 186 kg ha^{-1} of N, P and K, respectively, between two to eight months after planting compared to no fertiliser (Neilsen 1996). Similarly, application at planting of 18, 50 and 9 kg ha^{-1} of N, P and K, respectively, resulted in greater branch size in *Acacia* hybrid in southern Vietnam compared to a no fertiliser treatment (Bon and Harwood 2016). However in these same studies, there was a 72% increase in DBH and 22% increase in H at age 12 months in the *E. nitens* and *Acacia hybrid (Acacia mangium* × *A. auriculiformis)*, respectively. In the current study the growth difference between the 100 and 15 kg ha^{-1} of P treatments, although significant in *Eucalyptus* hybrid at age 12 months, was only 4% and 6% in DBH and H, respectively. While P fertiliser did not influence tree form in *A. mangium*, burning did lead to a significantly greater number of large branches, though not competing leaders in this species. In Malaysia, there were greater numbers of competing leaders in *A. mangium* following a burning treatment compared to a residue retention treatment; branch size was not measured (Eldoma et al. 2015). Compared to the burnt treatment, the more rapid development of weeds in the current study where residue was retained, particularly between ages 6 and 12 months (Hoang Van Thanh, pers. comm.), may have resulted in more competing vegetation which can suppress branch size (Petersen et al. 2008).

There have been limited studies linking plantation health to silvicultural practices in tropical eucalypts and acacia. In this study, a higher CDI was observed in the higher P treatment at planting in *Eucalyptus* hybrid, and in the burning treatment compared to residue retention in *A. mangium*. Damage from insect pests and diseases are often linked to a wide range of biotic and abiotic factors (Dell et al. 2012, Pinkard et al. 2010). One factor is the nutritional status of the host. Actively growing plants can rapidly develop canopies and regular flushes of new succulent leaves with a nutritional status favouring pest infestation (De Bruyn et al. 2002, Rashid et al. 2017). CDIs decreased from the top to the bottom position on the slope for both species which might be explained by differences along the slope in host vigour (De Bruyn et al. 2002) and/or access to the canopy by wind disseminated insect pests and fungal spores (Hardwick 2002). Although the average level of CDI across species and treatments was low and the effects on productivity are likely to have been small (Pinkard et al. 2006), it can be seen that there was an influence of different silvicultural treatments on the levels of pest damage and disease.

4.5. Conclusions

We concluded that the application of a high level of P fertiliser (100 kg ha^{-1} at planting) had little benefit on the growth of both *Eucalyptus* hybrid and *A. mangium* compared to the standard dose (15 kg ha^{-1}). The low amount of harvest residue and reasonably high fertility levels at the experimental site may have masked the response of tree growth to the residue-retention treatments. Poorer form in *A. mangium* following burning residue could increase production costs in plantations managed for sawlogs if more singling (removing multiple stems from trees to leave a single stem) and pruning is required. Harvest residue retention with adequate weed and termite control may be preferential to burning on a steep slope because the residue can reduce the speed of water run-off and soil erosion (Costantini and Lcoh 2002, Edeso et al. 1999, Oyarzun and Pena 1995).

Supplementary materials

Table 4.S1: Summary (P_value) of the two way analysis of variance (ANOVA) of survival, tree growth (DBH, H and V), leaf area index (LAI), tree form (number of leader branches and larger branches (> 10 mm)) and crown damage index (CDI) by residue management treatment and fertiliser application and their interaction at each age. Degree of freedom (df) for block, residue, fertiliser and residue×fertiliser were 4, 1, 1 and 1 respectively.

Stand age (month)	Measurements	*Eucalyptus* hybrid				*Acacia mangium*			
		Block	Residue	Fertiliser	Residue × Fertiliser	Block	Residue	Fertiliser	Residue × Fertiliser
6	Survival	0.529	0.445	0.644	0.645	0.107	0.046	0.208	0.519
	DBH	0.139	0.458	0.001	0.764	0.011	0.378	0.078	0.836
	H	0.714	0.476	0.014	0.991	0.025	0.254	0.066	0.926
	LAI	0.062	0.545	0.027	0.830	0.001	0.074	0.145	0.725
12	Survival	0.190	0.150	0.620	0.086	0.144	0.046	0.271	0.348
	DBH	0.330	0.646	0.018	0.405	0.007	0.166	0.951	0.730
	H	0.943	0.135	0.010	0.418	0.036	0.054	0.294	0.514
	V	0.518	0.528	0.056	0.937	0.009	0.020	0.827	0.928
	LAI	0.249	0.636	0.130	0.836	0.007	0.005	0.679	0.980
	Large_br	0.077	0.975	0.951	0.829	0.039	0.018	0.547	0.529
	Leader_br	0.461	0.396	0.097	0.086	0.085	0.263	0.358	0.092
	CDI	0.003	0.595	0.007	0.136	0.011	0.033	0.634	0.884
18	Survival	0.144	0.387	0.775	0.058	0.068	0.004	0.286	0.153
	DBH	0.110	0.409	0.149	0.366	0.956	0.512	0.269	0.491
	H	0.206	0.296	0.120	0.451	0.856	0.281	0.134	0.370
	V	0.437	0.507	0.065	0.988	0.853	0.091	0.388	0.996
	LAI	0.535	0.658	0.418	0.199	0.820	0.041	0.448	0.882
24	Survival	0.146	0.488	0.676	0.053	0.071	0.005	0.527	0.250
	DBH	0.112	0.197	0.345	0.205	0.450	0.177	0.234	0.729
	H	0.248	0.145	0.172	0.327	0.520	0.052	0.091	0.383
	V	0.284	0.248	0.609	0.177	0.272	0.018	0.229	0.974
	LAI	0.138	0.303	0.952	0.218	0.115	0.011	0.238	0.997

Notes: DBH, H, V, LAI, CDI were stem diameter at 1.3 m, tree height, standing volume, leaf area index and crown damage index, respectively. Large_br and leader_br were the number of large branches (>10 mm) and the number of leader branches per tree, respectively.

Table 4.S2: Foliar nutrient concentration (%) of *Eucalyptus* hybrid and *A. mangium* in experimental sites in northern Vietnam. No statistically significant different being observed between harvest residue management treatments or P fertiliser application treatments ($P > 0.05$), hence, mean values were presented.

Tree age	Nutrient	*Eucalyptus hybrid*				*A. mangium*			
		Residue management*		Fertiliser application**		Residue management		Fertiliser application	
		S0	S1	P15	P100	S0	S1	P15	P100
One year	N	1.55	1.65	1.50	1.70	2.83	3.03	2.97	2.89
	P	0.10	0.10	0.10	0.10	0.15	0.17	0.16	0.17
	K	0.37	0.33	0.33	0.57	0.44	0.96	1.00	0.38
	Ca	0.52	0.52	0.48	0.57	0.34	0.33	0.29	0.38
	Mg	0.14	0.14	0.13	0.15	0.11	0.11	0.11	0.11
Two years	N	2.20	2.23	2.10	2.33	2.54	2.55	2.69	2.40
	P	0.17	0.15	0.16	0.16	0.14	0.13	0.14	0.13
	K	0.47	0.59	0.45	0.61	0.32	0.30	0.34	0.28
	Ca	0.40	0.45	0.38	0.47	0.32	0.35	0.27	0.39
	Mg	0.15	0.15	0.13	0.17	0.11	0.14	0.13	0.12

[*] S0 and S1 are, respectively, burning and retention of residue treatment

[**] P15 and P100 are the low (15 kg ha^{-1}) and the high rate (100 kg ha^{-1}) of phosphorus fertiliser

Figure S4.1. A visual standard for estimating crown damage index of *Acacia mangium*

Defoliation: leaf 1 to 5. Percentage of leaf chew compared to total leaf area

Leaf 1 – 5%

Leaf 2 – 12%

Leaf 3 – 20%

Leaf 4 – 33%

Leaf 5 – 53%

Discolouration: leaf 6 to 11. Percentage of leaf discolouration compared to total leaf area

Leaf 6 – 3%

Leaf 7 – 6%

Leaf 8 – 10%

Leaf 9 – 19%

Leaf 10 – 50%

Leaf 11 – 75%

Necrosis: leaf 12 to 17. Percentage of leaf necrosis compared to total leaf area

Leaf 12 – 9%

Leaf 13 – 19%

Leaf 14 – 29%

Leaf 15 – 43%

Leaf 16 – 60%

Leaf 17 – 75%

CHAPTER 5

EFFECT OF HARVEST RESIDUE MANAGEMENT ON SOIL PROPERTIES OF *EUCALYPTYUS* HYBRID AND *ACACIA MANGIUM* PLANTATIONS PLANTED ON STEEP SLOPES IN NORTHERN VIETNAM

Article reference:

Bich, N.V., Eyles, A., Mendham, D., Evans, K.J., Dong, T.L., Hai, V.D., Thang, H.V., Thinh, N.V., Mohammed, C. Effect of harvest residue management on soil properties of *Eucalyptus* hybrid and *Acacia mangium* plantations planted on steep slopes of northern Vietnam. *Southern Forests, under review*.

CHAPTER 5. EFFECT OF HARVEST RESIDUE MANAGEMENT ON SOIL PROPERTIES OF *EUCALYPTYUS* HYBRID AND *ACACIA MANGIUM* PLANTATIONS PLANTED ON STEEP SLOPES IN NORTHERN VIETNAM

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This paper has been submitted to Southern Forests, under review

Abstract

Burning harvest residues during site preparation can compromise the soil-nutrient stock in short-rotation plantations, but this practice remains common in northern Vietnam. This study compared the effect of two contrasting harvest-residue treatments (burning *vs.* retention) on soil total carbon (TC), total nitrogen (TN), extractable P (ext-P), exchangeable K (exch-K) and bulk density (BD) of two adjacent randomized complete-block trials, one of *Eucalyptus* hybrid (*Eucalyptus urophylla* × *E. pellita*) and the other of *Acacia mangium* planted on steep slopes. Harvest-residue management had no effect on soil properties of either *E.* hybrid or *A. mangium* two years after planting. Soil pH in *E.* hybrid increased and exch-K in *A. mangium* decreased during the first year; ext-P decreased over time in both species though this was only significant in the residue-retention treatment in *A. mangium*. Slope significantly influenced pH and TC of *E.* hybrid and TC and TN of *A. mangium*. It appeared that slope position and correlative factors such as surface run-off and erosion had led to the observed distribution of some soil properties along the steep slope.

Keywords: burning post-harvest residues, site fertility, productivity, tropical plantation, sustainability, slope position

5.1. Introduction

In Vietnam, approximately 1.3 Mha of acacia (80%) and eucalypt (20%) plantations have been established in the past three decades (MARD 2010). Achieving sustainable wood over successive rotations is a major challenge for plantations managed on short rotations (5 to 8 years) to supply pulpwood and saw-logs (Dong et al. 2014, Harwood and Nambiar 2014, Nambiar et al. 2015). In short-rotation forestry, the inter-rotation phase between harvesting and replanting can be highly sensitive to site mismanagement (du Toit et al. 2010, Hoang et al. 2016, Laclau et al. 2010, Nambiar et al. 2015). In particular, the removal of harvest residues can have a negative influence on the sustainability of production (Achat et al. 2015, Gonçalves et al. 2008, Mendham et al. 2003, Rocha et al. 2016a). Repeated burning of residues following harvesting has been reported to contribute to site degradation in eucalypt and acacia plantations in Vietnam (Dong et al. 2014, Hung et al. 2017, Nambiar et al. 2015). This outcome is evident in northern Vietnam where much of the forest land is located on steep slopes (15–40°) and on soils that are dominated by acidic and leached acrisols of low to medium fertility (Hung et al. 2017, Phuong et al. 2012, Sang et al. 2013). In this study, the dynamics of soil properties following burning or retention of post-harvest residues were examined to provide an understanding of how best to sustain site fertility on steeply sloping sites.

Soil properties associated with residue management treatments have been examined in a number of hardwood plantations (Deleporte et al. 2008, du Toit et al. 2004, Huang et al. 2011, Huang et al. 2013, Kumaraswamy et al. 2014a, Little et al. 2000). Burning harvest residues has been shown to increase total soil P, and exchangeable soil K and Ca in the top soil (0 − 20 cm depth) of *Eucalyptus globulus* plantations in Australia (Mendham et al. 2003), *E. grandis* plantations in Brazil (Rocha et al. 2016a) and *Acacia mangium* plantations in Sumatra, Indonesia (Saharjo 1999). This observed increases in nutrient availability, probably due to the 'ash-bed effect' following burning (Chambers and Attiwill 1994, Giardina et al. 2000, Knoepp et al. 2004) may however, be short lived (Atwell et al. 1999), depending on the nutrient and site condition. In eucalypts, burning decreased soil nitrogen (TN) for up to two years (Mendham et al. 2003) and resulted in long-term losses of available P, K and Ca six years after establishment of the next rotation (Rocha et al. 2016a). These declines were associated with loss of organic matter and nutrients from the ecosystem via volatilisation during burning (Carreira and Niell 1995, Mendham et al. 2003, Trabaud 1994). In addition, large amounts of topsoil and nutrients may wash away from the site following burning due to surface run-off and erosion (Edeso et al. 1999, Oyarzun and Pena 1995). For example, in *Pinus taeda* planted on a $< 5^\circ$ slope, burning increased the loss of topsoil by 2.5× and the loss of soil TN, available Ca, Mg and K by 1.9, 2.6, 2 and 2×, respectively, compared to an un-burnt treatment (Field et al. 2003). Conversely, residue retention acts to conserve nutrients (Achat et al. 2015, Folster and Khanna 1997, Hernández et al. 2009) and protect the soil from run-off and erosion (Costantini and Lcoh 2002). Retention of residues is likely to be important for sustaining site fertility, especially in northern Vietnam where the soils are particularly vulnerable to erosion associated with heavy rainfall and surface run-off because of steep slopes and soil exposure (Orange et al. 2004, Phien et al. 2000, Trinh 2007).

The aim of this study was to compare the effects of burning (current operational practice) versus retention of harvest residues on soil properties in plantations of *A. mangium* and *Eucalyptus* hybrid (*Eucalyptus urophylla* × *E. pellita*) managed on steep slopes in northern Vietnam. In a complementary paper, Bich et al. (2019b) showed that there were no differences between the two treatments in the growth of either species. We hypothesised that the retention of harvest residues would benefit soil properties, especially on the steeper slopes, for both plantation species.

5.2. Materials and methods

5.2.1. Study site

The study site was located on steep slopes at Yen Bai province in Northern Vietnam (21°51'N, 105°00'E; 100 m above sea level) (Fig. 5.1).

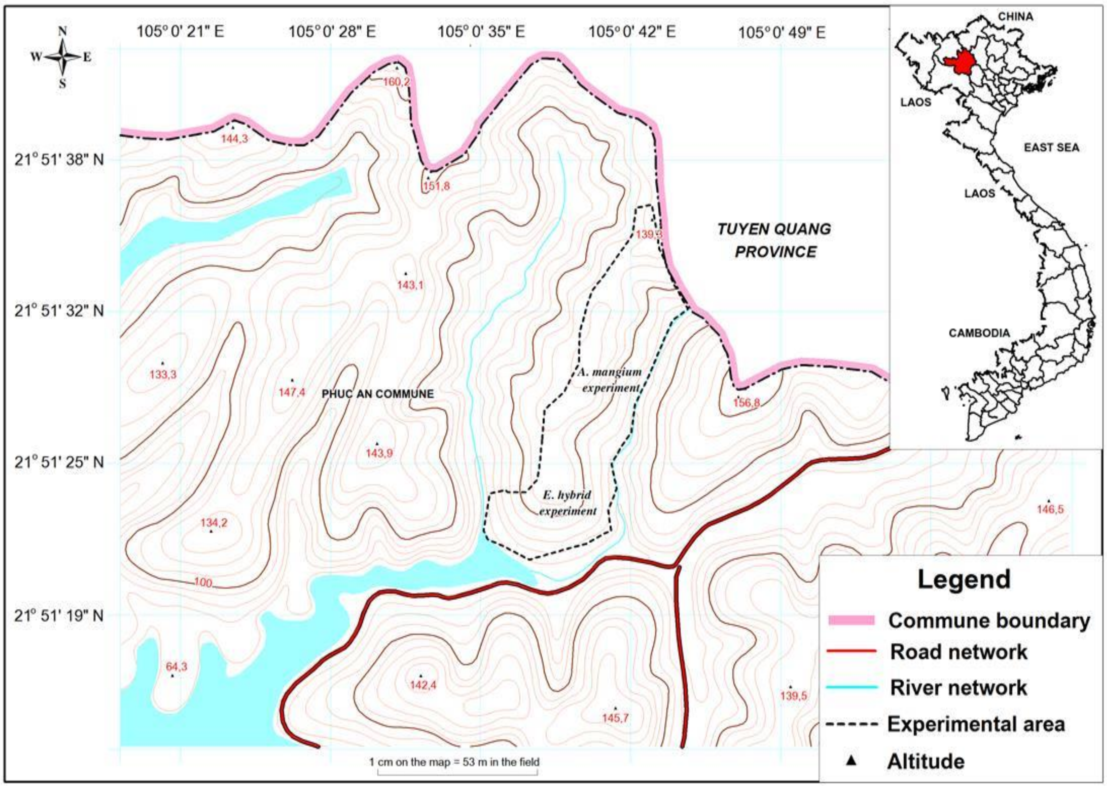

Figure 5.1. Map of study site and location of *E.* hybrid and *A. mangium* experiments in northern Vietnam

The climate is tropical with four distinct seasons. The mean monthly temperature ranges from 24 to 28℃ in summer, and from 15 to 21℃ in winter; rainfall is concentrated in summer (between May and September) and the mean annual rainfall is 1808 mm (Fig. 5.2).

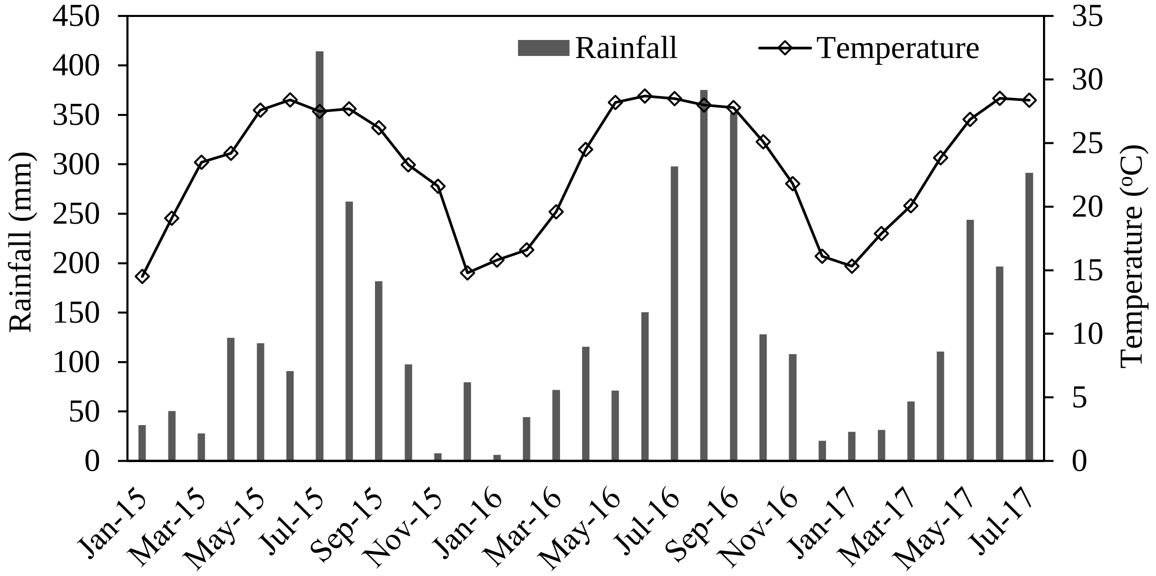

Figure 5.2. Average monthly temperature and rainfall during experimental period (Jan 2015-Jul 2017) in northern Vietnam.

The slopes of the experimental *A. mangium* and *Eucalyptus* hybrid (*E. urophylla* × *E. pellita*) plantations range from 5–10˚, 20–30˚ and 30–40˚ at the top- middle- and bottom-positions, respectively, with slope length of approximately 100 m and 150 m in *A. mangium* and *E.* hybrid, respectively. The soils are Ferric (Ferralic) Acrisols (FAO/UNESCO/ISRIC 1988) with a depth ranging from 100 cm at the top to 50 cm at the bottom of the slope. Soils (0–30 cm soil depth) are acidic with a mean soil pH (1:5 water) range from 3.9–4.0, and Bray II extractable P range from 2.2–3.1 mg kg^{-1} for both plantations (Table 5.1).

Table 5.1. Physical and chemical soil (0–30 cm soil depth) attributes before trial establishment of the *Eucalyptus* hybrid and *A. mangium* experimental sites in northern Vietnam. Values are the mean ± SE (n = 5).

Sand	Silt	Clay	pH	CEC	TC	TN	Ext-P	Exchangeable cations [$cmol_c$ kg^{-1}]		
(%)	(%)	(%)	1:5 water	($cmol_c$ kg^{-1})	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	K	Ca	Mg
***Eucalyptus* hybrid**										
30 (1.7)	23 (2.7)	47 (2.3)	4.0 (0.04)	10.0 (0.65)	22.0 (2.3)	2.0 (0.1)	2.2 (0.2)	0.08 (0.01)	0.18 (0.01)	0.24 (0.02)
Acacia mangium										
39 (1.2)	22 (0.8)	40 (1.5)	3.9 (0.05)	6.9 (0.6)	23.7 (2.4)	1.8 (0.1)	3.1 (0.4)	0.1 (0.01)	0.6 (0.12)	0.4 (0.08)

The land use history, the information of previous stand and the preparation of the experimental site were presented in Bich et al. (2019b). In brief, the site initially was degraded natural forest that was converted to *Styrax tonkinensis* (Pierre) Craib plantation in the 1980s, followed by two rotations of *A. mangium* planted in 2000 and 2008. Post-harvest residues were burnt during site preparation on each occasion. The second rotation of *A. mangium* was harvested at tree age 7 years (MAI = 13.3 ± 2.3 m^3 ha^{-1} yr^{-1}) in two separate operations – one half in January 2015 and the other half in April 2015 and then replanted with *Eucalyptus* hybrid in March 2015 or *A. mangium* in June 2015, respectively. The seedlings were planted in 30 × 30 × 30 cm planting holes with spacing of 2 × 3 m (1666 trees ha^{-1}) for *E.* hybrid, and 2.5 × 3 m (1333 trees ha^{-1}) for *A. mangium*. The planting stock was raised from seed for *A. mangium* (Balimo provenance) and from a mixture of four clones (UP54, UP72, UP95 and UP99) collected from a national seed orchard established by the Forest Tree Improvement and Biotechnology Research Institute, Vietnamese Academy of Forest Sciences, in Ba Vi, Hanoi. Across both experiments, 17, 15 and 8 kg ha^{-1} of N, P and K was applied at planting hole at planting (see detail in Bich et al. (2019b)). Weeds were completely controlled, using a wood-handle machete, every six months until canopy closure.

5.2.2. Experimental design and layout

In December 2014, biomass of harvest residues was estimated for each component (Bich et al. 2018). In brief, the total initial dry weight of all residues was 27.2 Mg ha^{-1} including harvest residue (branches + leaves + bark, 18.1 Mg ha^{-1}) and forest floor (litter + understorey vegetation, 9.1 Mg ha^{-1}). At establishment, all residues were distributed evenly prior to planting; they were estimated to contain 440 kg ha^{-1} of N, 15 kg ha^{-1} of P, 61 kg ha^{-1} of K, 185 kg ha^{-1} of Ca and 20 kg ha^{-1} of Mg. Compared to the level of soil pools (0 – 10 cm soil depth) at this site, the amounts of N and P content in all residues accounted for 25% and 9% of the total soil N and P, respectively. However, compared to the available values, the content of P in all residues accounted for 442% of available soil P, while the content of K, Ca and Mg accounted for 132%, 157% and 44% of available soil K, Ca and Mg, respectively.

The effect of residue management (burning *vs.* retention) and fertiliser application (P15: 15 kg of P per ha *vs.* P100: 100 kg P per ha) on tree growth and soil properties was examined with a randomised complete block design with five replications and layout of the main experiment that tested as described in Bich et al. (2019b). The replicate blocks were arranged to account for the three slope positions. Ten plots for each species were sampled to assess the effect of harvest residue burning or retention on soil properties, comprising five plots of each of the following treatments:

(1) S0: residues burnt and 15 kg ha^{-1} of P: harvest residues evenly distributed throughout the plots, then all residues including litter and understorey subsequently burnt 60 days after clear-cutting and two weeks before planting.

(2) S1: residues retained and 15 kg ha^{-1} of P: harvest residues evenly distributed throughout the plots.

The total experimental area for both species was 1.4 ha, including 0.6 ha (10 gross plots, 30 m × 20 m) for *E.* hybrid and 0.8 ha (10 gross plots, 30 m × 25 m) for *A. mangium*. The experimental measurements were made on net plots of six rows of six trees each to provide areas of 216 m^2 and 270 m^2 for *E.* hybrid and *A. mangium*, respectively. Each net plot was surrounded by two buffer rows on each side.

5.2.3. Soil sampling and analysis

In each plot, five soil samples were collected randomly at 0–10 cm depth with an auger at establishment and at ages one and two years after planting; these samples were pooled before analyses of chemical properties. For soil bulk density, a further five samples of undisturbed soil cores were collected randomly in each plot using a 53 mm diameter × 51 mm length cylinder.

Soil samples were air-dried and passed through a 2 mm mesh sieve, followed by oven-drying at 65 °C to constant weight. Soil chemical properties were analysed via standard methods based on van Reeuwijk (2002): total C by wet oxidation (Walkley-Black), total N by Kjeldahl, soil exchangeable K by ammonium acetate method – 1 M $NH_4CH_3CO_2$ at pH 7.0, and soil pH (in 1:5 soil-water ratio). Soil available P was analysed by the Bray II method (Bray and Kurtz 1945). Soil bulk density was determined from cores that had been dried at 105 °C to constant weight.

5.2.4. Statistical analysis

One-way analysis of variance (ANOVA) was used to test the variation in pH, TC, TN, extractable P, exchangeable K and soil bulk density (BD) between the two types of residue treatment (burning *vs.* retention) using the initial soil properties as a covariate to account for inherent spatial variation. Differences in response between the two types of residue treatment at ages one or two years compared to the initial level was assessed using a paired sample t-test (n = 5). The effect of slope (which was used as a surrogate for position in the landscape) and residue treatment on soil properties was examined using analysis of covariance and regression. Statistical tests were conducted with SPSS for Windows version 22.0 (IBM Corp, 2013).

5.3. Results

5.3.1. Effect of residue management treatments and sampling times on soil properties

Harvest-residue treatment had no significant influence on soil properties in either the *E.* hybrid or *A. mangium* plantation 1 and 2 years after planting (data not shown). However, sampling time had a significant effect on some soil properties (Table 5.2).

Table 5.2. Changes in soil chemistry between establishment and one year (T1-T0), establishment and two years (T2-T0) in *E.* hybrid and *A. mangium* in northern Vietnam. The data show the mean value of the differences between sampling times with standard errors in parentheses (n = 5). Asterisks indicate statistical significance of changes (i.e. ** $p \leq 0.01$; * $p \leq 0.05$; ns, not significant) by using a paired sample t-test.

Soil properties	Burning				Retention			
	T1-T0	*P*-value	T2-T0	*P*-value	T1-T0	*P*-value	T2-T0	*P*-value
***Eucalyptus* hybrid**								
pH(1:5 water)	0.51 (0.07)	**	-0.10 (0.09)	ns	0.47 (0.09)	**	0.05 (0.03)	ns
TC (g kg^{-1})	0.15 (4.80)	ns	3.34 (3.83)	ns	-1.91 (4.09)	ns	2.49 (5.95)	ns
TN (g kg^{-1})	-0.30 (0.19)	ns	0.06 (0.31)	ns	-0.34 (0.26)	ns	0.06 (0.16)	ns
Ext-P (mg kg^{-1})	-1.46 (0.48)	*	-0.72 (0.57)	ns	-0.96 (0.60)	ns	-0.70 (0.36)	ns
Exch-K (mg kg^{-1})	0.00 (0.01)	ns	-0.02 (0.02)	ns	0.00 (0.02)	ns	0.00 (0.01)	ns
BD (g cm^{-3})	0.05 (0.03)	ns	0.04 (0.04)	ns	0.06 (0.04)	ns	0.01 (0.03)	ns
Acacia mangium								
pH(1:5 water)	0.02 (0.03)	ns	0.06 (0.05)	ns	0.01 (0.10)	ns	-0.02 (0.07)	ns
TC (g kg^{-1})	-3.75 (4.08)	ns	1.95 (4.05)	ns	-7.41 (4.40)	ns	1.06 (6.19)	ns
TN (g kg^{-1})	0.12 (0.19)	ns	-0.08 (0.12)	ns	-0.04 (0.15)	ns	0.14 (0.23)	ns
Ext-P (mg kg^{-1})	0.67 (0.72)	ns	-1.08 (0.72)	ns	0.82 (0.98)	ns	-2.29 (0.81)	*
Exch-K (cmolkg^{-1})	-0.05 (0.02)	*	0.00 (0.02)	ns	-0.05 (0.01)	*	-0.01 (0.02)	ns
BD (g cm^{-3})	0.09 (0.06)	ns	0.02 (0.08)	ns	0.03 (0.06)	ns	0.04 (0.06)	ns

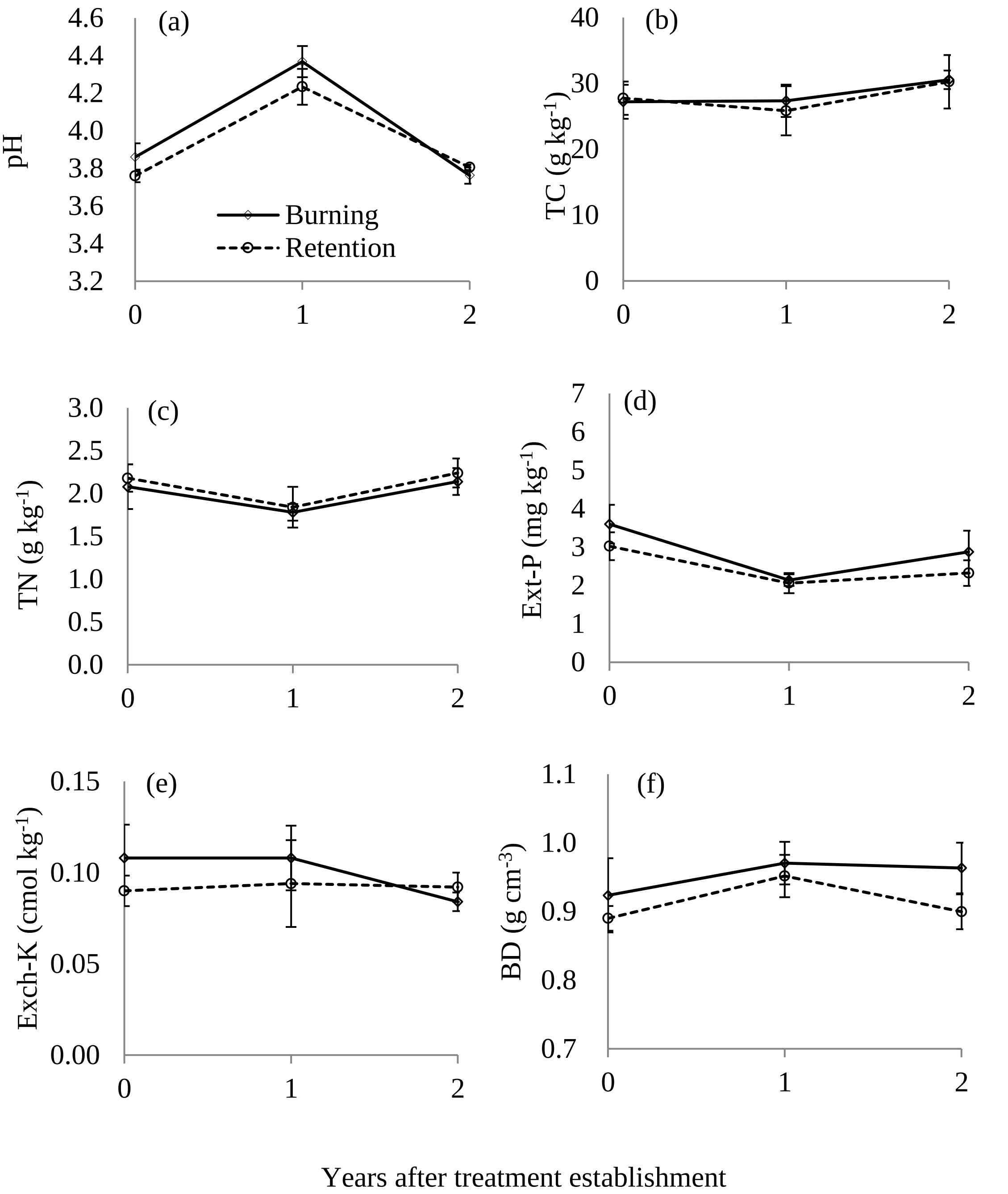

Figure 5.3. Soil $pH_{(1:5\ water)}$ (a), soil organic carbon (TC) (b), total nitrogen (TN) (c), extractable P (ext-P) (d), exchangeable K (exch-K) (e) and soil bulk density (f) under two contrasting residue management treatments (burning *vs.* residue-retention) over two years following planting of *Eucalyptus* hybrid at an experimental site in northern Vietnam. Error bars represent ± 1 standard error of the mean (n = 5). There was no statistically significant difference (P > 0.05) of the soil properties between treatments at age one and two years following planting.

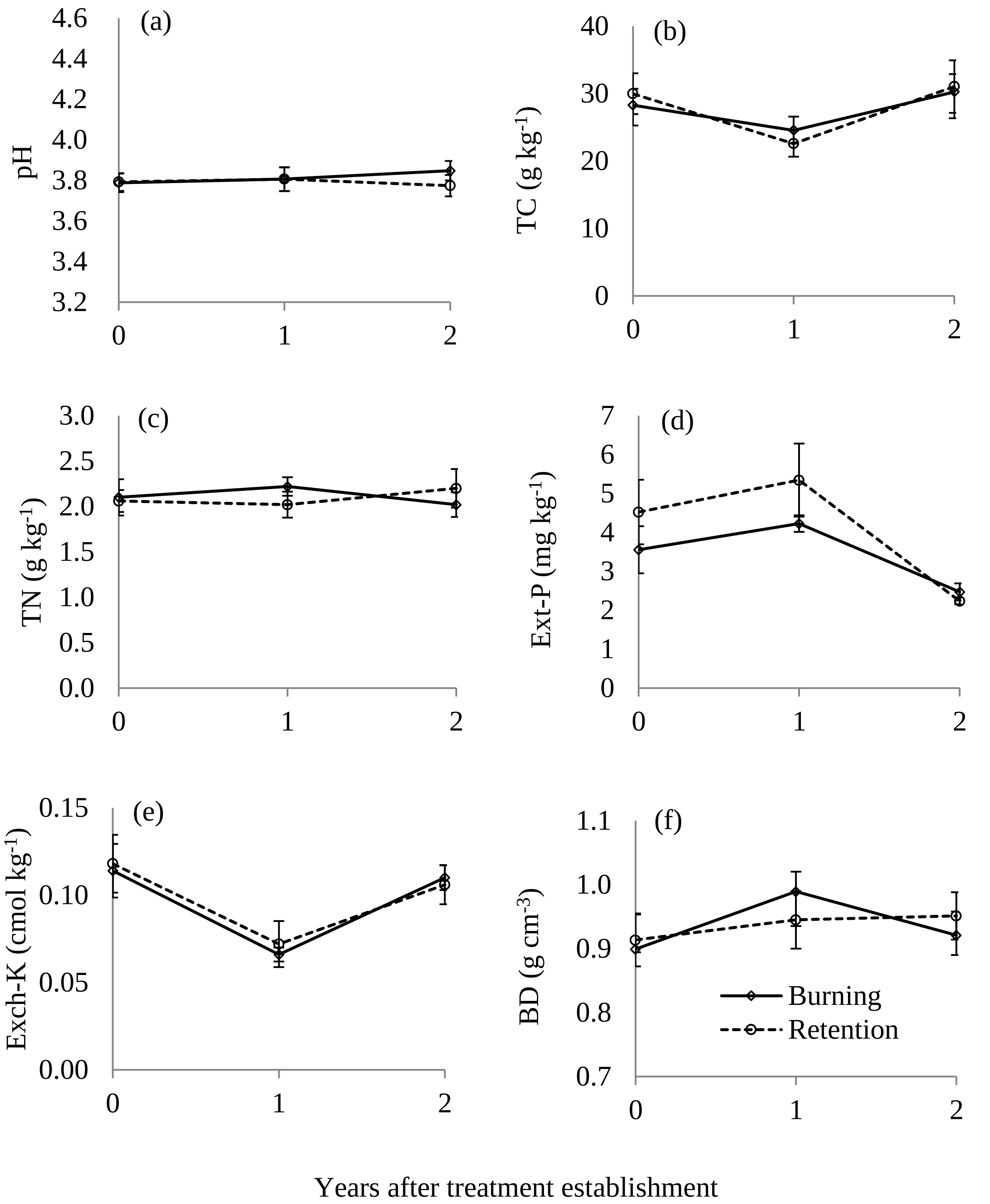

Figure 5.4. Soil $pH_{(1:5\ water)}$ (a), soil organic carbon (TC) (b), total nitrogen (TN) (c), extractable P (ext-P) (d), exchangeable K (exch-K) (e) and soil bulk density (f) under two contrasting residue management treatments (burning *vs.* residue-retention) over two years following planting in *Acacia mangium* at an experimental site in northern Vietnam. Error bars represent ± 1 standard error of the mean (n = 5). There was no statistically significant difference (P > 0.05) of the soil properties between treatments at age one and two years following planting.

During the first year, soil pH in the *E.* hybrid plantation significantly increased (*P* < 0.01, Fig. 5.3a, Table 5.2) and exch-K in the *A. mangium* plantation significantly decreased (*P* < 0.05, Fig. 5.4e, Table 5.2); these soil properties recovered to approximately their initial level two years after planting. Soil ext-P in the *E.* hybrid and *A. mangium* plantations decreased by 0.70–0.72 mg kg^{-1} and 1.08–2.29 mg kg^{-1}, respectively, between establishment and age two years (Table 5.2), though this was only statistically significant (*P* < 0.05) in the residue-retention treatment in *A. mangium* (Fig. 5.4d, Table 5.2).

5.3.2. Effect of slope on soil properties at age 2 years

The relationships between slope and soil properties were not influenced by harvest residue- treatment for either *E.* hybrid or *A. mangium*. In the *E.* hybrid plantation, there was a significant reduction in TC with increasing slope (*P* < 0.05, Fig. 5.5b). In the *A. mangium* plantation, there was a significant increase in pH and a significant reduction in TC and TN with increasing slope (0.001 < *P* < 0.05, Fig. 5.6a, b, c).

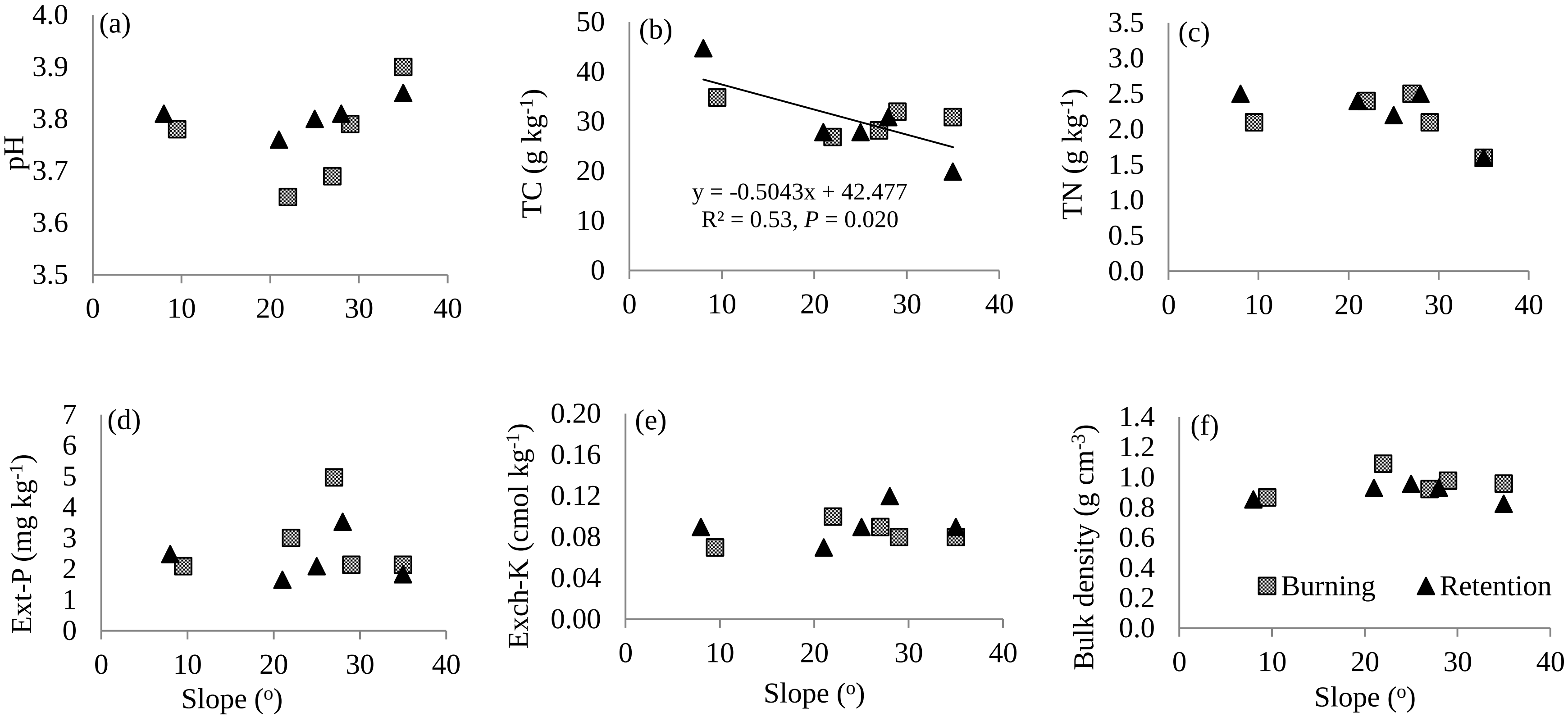

Figure 5.5. Relationship between slope and soil properties (0-10 cm soil depth) including soil pH (a), organic carbon (TC) (b), total nitrogen (TN) (c), extractable P (Ext-P) (d), exchangeable K (exch-K) (e) and soil bulk density (f) of an *E.* hybrid plantation at tree age two years in northern Vietnam. (Note that: pH: y = 0.0118x + 3.4525 (R^2 = 0.60, *P* = 0.029) when excluding two outlier values from the top of the hill (slope = 10 °)

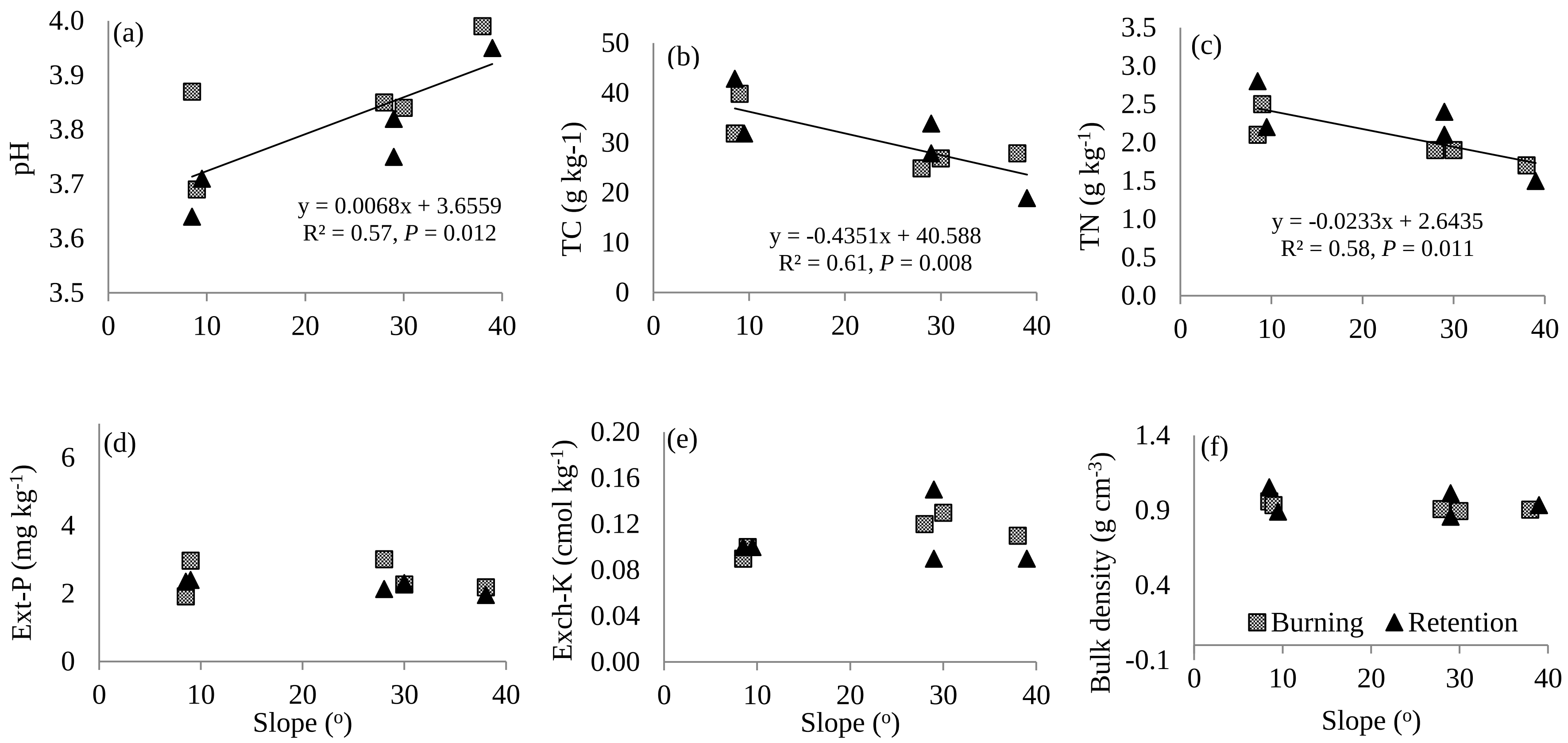

Figure 5.6. Relationship between slope and soil properties (0-10 cm soil depth) including soil $pH_{(1:5\ water)}$ (a), organic carbon (TC) (b), total nitrogen (TN) (c), extractable P (Ext-P) (d), exchangeable K (exch-K) (e) and soil bulk density (f) of an *A. mangium* plantation at tree age two year in northern Vietnam.

5.4. Discussion

Burning of harvest residues following harvesting appeared to have had no negative impact on the measured soil properties of either the *E.* hybrid or *A. mangium* plantation in the two years following establishment. There was some evidence that ext-P decreased over time whether the harvest residue was retained or burnt. Slope angle influenced some soil properties. These results are now discussed in the context of suitable residue-management practices for sustaining site fertility of eucalypt and acacia plantations planted on steep slopes.

The lack of an effect of residue treatment on soil properties may be because the quantity of post-harvest residues, 27 t ha^{-1} (Bich et al. 2018), was low compared to what has been found previously for acacia plantations in the tropics. Values of 38–135 t ha^{-1} have been reported elsewhere (Hardiyanto and Nambiar 2014, Huong et al. 2015, Siregar et al. 2008). That findings of minimal impact of residue treatments on soil properties was also supported by a study in *Eucalyptus tereticornis* and *E. grandis* in Kerala, India, post-harvest residues ranging from 27 to 40 t ha^{-1} (Sankaran et al. 2005), of which soil organic carbon, N and P content in 0-5, 5-10 and 10-20 cm soil depth were not different between removal and retention of harvest residue treatment (Kumaraswamy et al. 2014a). Similarly, Mendham et al. (2003) were not able to measure many significant differences in soil properties (in 0-5 and 5-20 cm), between the residue treatments, even in the double-residue treatment with higher residue loads (up to 100 t ha^{-1}). Burning is normally associated with a significant increase in ext-P and exch-K because of the transformation of organic matter into nutrient-rich ash, and a reduction of TC and TN because of volatilisation (Giardina et al. 2000, Raison et al. 1985b). The relatively small quantities of harvest residue may not have been sufficient to generate temperatures that would lead to such transformations (Certini 2005, Giardina et al. 2000).

Soil pH in both treatments increased significantly by around 0.5 units during the first year in the *E.* hybrid plantation. Increases in nutrient availability following burning (Gonçalves et al. 2007, Mendham et al. 2008) and decomposition of harvest residues (du Toit et al. 2008, Tiarks and Ranger 2008) can be associated with such an increase. A higher production of litterfall in the *E.* hybrid than *A. mangium* plantation at age one year (unpublished data) may help to explain why no changes in pH were found in the *A. mangium* plantation. The recovery of soil pH in the *E.* hybrid plantation two year following planting may be associated with uptake of cations by the growing stand (Chambers and Attiwill 1994) and the rate of harvest residue decomposition (Bich et al. 2018).

In the *A. mangium* plantation, soil exch-K decreased by 58% between establishment and age one year. Although K is easily lost by leaching (Nambiar and Brown 1997), rates of uptake by fast-growing trees are generally high, as much as 28 and 95 kg ha^{-1} yr^{-1} in eucalypt and acacia plantations, respectively, in the first year of growth (Hardiyanto and Nambiar 2014, Laclau et al. 2003). Two years following planting, exch-K in the *A. mangium* plantation returned to their values at planting, probably due to a reduction in K uptake by growing trees (Hardiyanto and Nambiar 2014) and increase in the amounts of K released from post-harvest residue and litterfall.

Levels of ext-P declined over time with the effect being significant for *A. mangium*. The decline of soil P in *A. mangium* but not in *E.* hybrid plantation may be due to a higher demand for P by *A. mangium* as a leguminous species (Inagaki et al. 2009), requiring a greater demand on the soil P reserve. Reduced available P is a common observation in tropical acacia plantations (Hardiyanto and Wicaksono 2008, Huong et al. 2015, Nykvist 1996, Siregar et al. 2008) and partly attributable to the uptake of P by growing trees – approximately 7.5 kg ha^{-1} yr^{-1} in *A. mangium* stands in the first two years following planting (Hardiyanto and Nambiar 2014). Because of the steep slopes of the site, additional loss of soil P may be due to runoff and erosion (Hussein et al. 1999), especially in the burning treatment (Field et al. 2003). In the residue-retention treatment, there was some evidence that soil P was immobilised in decomposing harvest residues, particularly in branches and bark (Bich et al. 2018). As this immobilised P can be released for uptake by trees at a later stage (Crockford and Richardson 2002, da Silva et al. 2015), in the longer term, residue retention rather than burning is more likely to sustain levels of soil P.

While soil properties (and the growth variables; see Bich et al. (2019b)) of both species were not influenced by harvest-residue management, significant relationships between slope (as a surrogate for position on the slope) and some of the soil properties indicate that slope position can have an important influence on the productivity of the plantations, consistent with previous studies (Harwood et al. 2017). In the *E.* hybrid plantation, TC was significantly higher on the shallower slopes at the top of the hill than in the middle and bottom positions, and for both TC and TN in the *A. mangium* plantation. This may have been the result of previous topsoil erosion (Polyakov and Lal 2004) associated with poor practices (burning/removal of harvest residues) in previous rotations. Although soil erosion was not measured in this study, the upper slope positions are likely to be less eroded than middle and lower slope positions, owing to the lesser slope angle and shorter slope length (Bagio et al. 2017, Liu et al. 2000, Wezel et al. 2002). In the *A. mangium* plantation pH was highest at the bottom of the hill, probably as a result of the downslope leaching of soluble base cations (Barbour et al. 2007). Although residue management had no effect on the measured soil properties, burning inevitably leads to soil exposure, and is therefore more likely to leave the soil vulnerable to erosion and soil loss.

5.5. Conclusions

We did not detect any effect of harvest residue burning on TC, TN, exch-K or BD in soil with either *E.* hybrid or *A. mangium* planted on steep slopes over the two-year study period. The lack of response may have been due to the relatively low quantity of post-harvest residues, which may have masked the potential effect on soil properties of the treatments used in this study. However, a measured decline in soil P suggests that this nutrient may become the most limiting in this environment where most soils already have low available P. The significant decrease in TC and TN from the top to the bottom of the slope suggests that slope position and factors correlating with slope such as surface runoff and erosion may have been the cause of the observed changes in soil properties.

CHAPTER 6

GENERAL DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

CHAPTER 6. GENERAL DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

The research set out to determine, for eucalypts and acacia planted on steep slopes in Vietnam, the pros and cons of burning or retaining harvest residues and the application of high levels of P at planting in relation to achieving sustainable production.

I examined, at a steeply sloping site in northern Vietnam following the harvesting of a seven-year-old commercial *A. mangium* plantation, the quantity of harvest residues (branches, leaves and bark), litter and understorey vegetation maintained on the site. I determined the rates of decomposition and nutrient release from the decomposing harvest residues. In addition, at the same site, I investigated the effect of two residue management regimes (burning *vs.* retention of post-harvest residues) on soil properties. I analysed the potential impact on the productivity of *E.* hybrid and *A. mangium* plantations of the interactions between the two harvest residue management regimes and two different levels of P fertiliser application (15 *vs.* 100 kg P ha^{-1}).

In my study, burning or the retention of post-harvest residue treatment had no apparent effect on the growth and soil properties of both *E.* hybrid and *A. mangium* plantations although significant amounts of macro-nutrients, especially N, K and Ca, were released from decomposing harvest residues over the 1.5 year study period. Two years after planting, a higher level of P fertiliser applied at planting did not lead to additional gains in productivity in either tree species when compared to the lower P treatment. There was evidence of slope effect on certain soil properties and productivity.

In this chapter, I will examine the key findings of this thesis in the context of improving inter-rotational management practices, specifically post-harvest residue management and fertiliser application at planting. I will discuss the potential impact of these results on the sustainable management of site fertility and productivity of tropical eucalypt and acacia plantations planted on steep slopes. Finally, I will suggest some directions for future research.

6.1. General discussion

6.1.1. Quantity of biomass and nutrient content in post-harvest residues maintained on the site following harvesting

In this study, the total quantity of post-harvest residues maintained on the site following the harvesting of a seven-year-old *A. mangium* was 27.2 t ha^{-1}. The total load of residue at the site was comprised of 66% harvest residues (branches, leaves and bark), 21% litter and 13% understorey vegetation. This quantity was relatively low for tropical acacia plantations which typically range from 38 – 135 t ha^{-1} (Hardiyanto and Nambiar 2014, Huong et al. 2015, Siregar et al.). The lower quantity is related to the poor productivity of the plantation harvested at this site (MAI = 13.32 ± 2.26 m^3 ha^{-1} yr^{-1}) compared to other sites (MAI ranged from 18.6 – 29.7 m^3 ha^{-1} yr^{-1}) (Hardiyanto and Nambiar 2014, Huong et al. 2015).

The quantities of macro-nutrient in post-harvest residues were estimated to be 440 kg ha^{-1} of N, 15 kg ha^{-1} of P, 61 kg ha^{-1} of K, 185 kg ha^{-1} of Ca and 20 kg ha^{-1} of Mg. Compared to the level of soil pools (0 – 30 cm soil depth) at this site, the amounts of N and P content in post-harvest residues only accounted for 9% and 6% of the total soil N and P respectively. However, compared to the available values, the content of P in post-harvest residues accounted for 187% of available soil P, while the content of K, Ca and Mg accounted for 48%, 52% and 14 % of available soil K, Ca and Mg, respectively. The results indicated that even small quantities of post-harvest residues as in this study can conserve significant amounts of macro-nutrients for recycling especially P.

The retained bark on site at harvesting in this study made up one-third of the mass of post-harvest residues and conserved 6% Mg, 14% K, 18% P, 30% N and 41% Ca content for recycling. Other studies have shown that the removal of bark from a site at harvesting significantly reduces the quantity of post-harvest residues (Achat et al. 2015, Hardiyanto and Nambiar 2014, Huong et al. 2015). The bark of *A. mangium* in Vietnam accounts for 15% (Chapter 3, see also Hai et al. (2009a)) of total stand above ground mass (AGB). This is proportionately higher than that observed in other species including other acacia species, eucalypts and pines (typically ranging from 7 – 12% of stand AGB) (du Toit et al. 2004, Hai et al. 2009a, Hardiyanto and Nambiar 2014, Hernández et al. 2009, Huong et al. 2015, Li et al. 2011, Santana et al. 2000). My results highlight that the current practices in Vietnam when bark is removed from the site with the commercial logs, or stripped after harvesting at the edge of the site or in a nearby wood yard, and not distributed over the logging area is likely to compromise the productivity potential of the site.

Retention of post-harvest residues, even of a smaller amount of residue as in this study, appears crucial for sustaining site fertility of tropical plantations especially as most of the plantation soils are currently low in available P (Dong et al. 2014, Hardiyanto and Nambiar 2014, Nambiar and Brown 1997). Retention of bark on site for *A. mangium* plantations may also be an important consideration for the sustainable production of this species.

Foliage nutrient concentration is an important indicator to identify nutrient limitation in plants (Judd et al. 1996). In this study, the foliage N, P, K, Ca and Mg concentration of *A. mangium* in previous stand were 2.99%, 0.18%, 0.51%, 0.54% and 0.11%, respectively, suggests that P, K and Mg appear to be at deficiency level for *A. mangium* (Reuter and Robinson 1997). In the new *Acacia mangium* seedling, foliage nutrient concentration ranged from 2.8-3.0% for N, 0.15-0.17% for P, 0.30-0.32% for K, 0.32-0.35% for Ca and 0.11-0.14 for Mg (Chapter 4) at age two years, indicating that K and Mg were the limiting nutrients for tree growth in this condition (Reuter and Robinson 1997). Hence, it appears that P, K and Mg are the most critical nutrient for sustaining productivity of the plantation in this environment.

6.1.2. Decomposition rates and nutrient release from A. mangium harvest residues

Harvest residues retained on site in the form of bark, branches and leaves (i.e. not including litter and understorey vegetation) accounted for two-thirds of the total initial dry weight and 24 – 64% of the macro-nutrient content of post-harvest residues. The rates of decomposition and nutrient release from harvest residues varied between its components reflecting the variation of their substrate quality, especially in relation to the concentration of N (Chapter 3). Among harvest residue components, the decomposition rate of the leaves was the most rapid (k = 1.47 year^{-1}; $t_{0.5}$ = 0.47 year), then branches (k = 0.54 year^{-1}; $t_{0.5}$ = 1.29 year) and bark (k = 0.22 year^{-1}; $t_{0.5}$ = 3.09 year). The highest concentration of N was in leaves, then in the branch and bark components. The decomposition rates of *A. mangium* harvest residues in this study were faster than those observed for eucalypts and pines in other studies (Garrett et al. 2010, Hernández et al. 2009, Shammas et al. 2003). These higher rates of decomposition are partly attributable to the higher N concentration in *A. mangium* harvest residues (Chapter 3). In addition, higher temperatures and moisture in the tropical climate of Vietnam are factors that will cause faster rates of decomposition (Parton et al. 2007, Song et al. 2012, Zhang and Wang 2015). Thus, harvest residues from tropical acacia plantations appear to release nutrients, especially N, more rapidly than other species.

During decomposition, the loss of nutrients from harvest residues was K ≈ Ca > N > P> Mg. Over the 1.5 year study period, as much as 137.1 kg N ha^{-1}, 4.7 kg P ha^{-1}, 20.8 kg K ha^{-1}, 94.5 kg Ca ha^{-1} and 2.2 kg Mg ha^{-1} was recycled from decomposing *A. mangium* harvest residues. Based on the quantities of nutrient uptake by tropical acacia and eucalypt trees (Hardiyanto and Nambiar 2014, Laclau et al. 2003), the N, Ca and K, though not P and Mg released from decomposing *A. mangium* harvest residues has the potential to meet a significant part of the demand by trees growing in the next rotation although the amount of N and K lost by leaching or fixation in a tropical soil remains unknown. A high quantity of N released, but not P, might cause a nutrient imbalance. As P supply is crucial to the growth of acacia, the addition of P fertiliser at planting is recommended, both to boost immediate supply and to potentially enhance decomposition rates of the harvest residues.

6.1.3. Residue management and its impact on soil properties and productivity of short-rotation commercial plantations on steep slopes

There was a reduction in soil carbon and nutrient content (including ext- P and exch-K) following planting (Chapter 5) in both treatments, most likely an immediate impact of clear cutting and re-establishing a plantation. This may be explained by the loss of topsoil as found in other studies (Dong et al. 2014, Nambiar et al. 2015). Burning residue during site preparation leads to soil exposure, thus potentially increases the loss of nutrients and there was only a low amount of harvest residues in this study (Chapter 3) to act as a nutrient or erosion buffer. Burning residue is most often associated with initial increases quantities of nutrients released to the site (Deleporte et al. 2008, Laclau et al.

2010, Mendham et al. 2003). This was not the case in this study and soil properties were no different between the burning and residue retention treatments during the two years following establishment. Nutrients following burning, especially on the steep slope studied, could have been lost by leaching, surface runoff and erosion (Dovey et al. 2014, Field et al. 2003). Steep slopes which experience high rainfall as in this study are highly vulnerable to erosion (Orange et al. 2004, Phien et al. 2000, Trinh 2007).

The fact that there were no observed differences in growth responses between residue management treatments (burning or retention) in this study may, similarly to the lack of difference in soil properties, be due to the low amount of harvest residues (Chapter 3) and reasonably high fertility levels existing at the experimental site (Chapter 4). Responses of growth to different residue management treatments have been studied in many plantations (Gonçalves et al. 2007, Hardiyanto and Nambiar 2014, Huang et al. 2013, Huong et al. 2015, Rocha et al. 2016a) and it is clear that the responses in this study are atypical and probably site specific. Burning post-harvest residues often leads to better initial tree growth (DBH, H and V) than other harvest residue treatments, probably due to the nutrients returned to the soil from ash following burning (du Toit 2008, Gonçalves et al. 2007). This initial positive influence of burning residue however may be transient compared to harvest residue retention (Rocha et al. 2016a). The MAI of acacia and eucalypt plantations has been found to have a positive correlation with fairly high quantities of residue maintained on site following harvesting (Deleporte et al. 2008, Huong et al. 2015).

Although tree growth was not significantly influenced by residue management treatments the treatments impacted other observed parameters. Harvest residue burning in *A. mangium* resulted in a larger number of large branches per tree since the retained residue probably suppressed to some extent the formation of large branches. Large branches when pruned can lead to defect and thus an issue for trees destined for solid wood production. The CDI in *A. mangium* was higher (i.e. the crown was less healthy) in the burnt residue than in the residue-retention treatment possibly because of greater exposure of the crown to the environment in the early stages of development. Tropical acacias are also highly susceptible to termite damage, a problem that is exacerbated by residue retention (Ngoc et al. 2011) as also shown in this study where there was most likely less survival in the retained treatment. In addition to the termites, residue-retention treatment may have promoted more rapid weed development (Hoang Van Thanh; pers. comm.).

The significant correlations between slope position, tree growth and certain soil properties (e.g. TN and TC) suggest that slope position strongly influenced soil properties and productivity of the plantations in this study. Factors driving any correlation of tree productivity and soil properties with slope, for example surface run-off and soil erosion (Bagio et al. 2017, El Kateb et al. 2013, Sidle et al. 2006) will need careful management to arrest potential yield decline on steeply sloping sites. In this context and balancing the trade-offs explored in this study, residue retention is preferential to burning on a steep slope because the residues has been shown to conserve nutrients in situ, increase infiltration (Khan et al. 2016, Ruan et al. 2001, Ward Philip et al. 2015) and reduce overland flow (Costantini and Lcoh 2002, Edeso et al. 1999, Oyarzun and Pena 1995) that can minimise the loss nutrients due to leaching, runoff and erosion (Field et al. 2003). Harvesting in the dry season and shortening the period of replanting of new plantation can minimise the impact of surface runoff and decrease loss of topsoils during inter-rotation period. This study also highlights that managers must consider effects of management strategies on potential weed development and biotic damage. Allowing a reasonable amount of weed during re-establishment of the new plantation may increase vegetation coverage, hence can also reduce the loss of topsoil, especially during rainy season but needs to balance against the negative effect of weed competition.

6.1.4. Effect of fertiliser application at planting on productivity of short-rotation eucalypt and acacia plantations

Fast-growing short-rotation plantation species generally require a large amount of nutrients to optimize yield (Folster and Khanna 1997). The amount of nutrient uptake by tropical acacia and eucalypt trees is generally highest during the first three years after planting (Hardiyanto and Nambiar 2014, Huong et al. 2015, Leite et al. 2011); approximately 82 – 180, 7 – 12, 29 – 80, 44 – 90 and 23 – 39 kg ha^{-1} $year^{-1}$ of N, P, K, Ca and Mg, respectively, were accumulated in the above-ground stand biomass at age two years (Hardiyanto and Nambiar 2014, Laclau et al. 2003). Hence, application of fertiliser at planting is a common practice in commercial plantations and often improves the productivity (Folster and Khanna 1997, Forrester et al. 2010, Gonçalves et al. 2004).

In this study, the growth and LAI of the *A. mangium* were not significantly different between the high and low level of P (100 *vs.* 15 kg P ha^{-1}) during the two-year-study period (Chapter 4). The quantity of P required for optimum growth response of tropical acacias is often reported as low (Hardiyanto and Nambiar 2014, Huong et al. 2015, Mendham et al. 2017). Compared to acacia, eucalypts may require large amount of P to maximise the growth rates (Judd et al. 1996), especially in low soil available P sites (Melo et al. 2016, Xu et al. 2005). High P applied at planting can be used to stimulate more rapid early establishment of eucalypt plantations and may bring forward the harvest age at some sites, but its relative effect compared to a lower application of P is likely to decline with stand age, and as with this study, it can disappear entirely. A high dose of P applied at planting was also associated with the greater crown damage index caused by fungal diseases in eucalypt (Chapter 4) and could be attributed luxury consumptions of P influencing host pathogen interactions (Altieri and Nicholls 2003, Carnegie and Ades 2001, Dordas 2008).

Although responses to application of calcium (Ca) and potassium (K) has not been observed in acacia plantations to date (Hardiyanto and Wicaksono 2008; Huong et al. 2008), successive wood harvests will gradually deplete cations from the soil, at higher rates if total biomass is removed at each harvest, and may induce deficiencies over time (Gonçalves et al. 2013). The results of foliage nutrient concentration in this study showed that the phosphorus levels for all treatments and both years are adequate. However, accepting a required level of 0.6% stands are K limited in the second year and magnesium (Mg) is low or marginal (Mead and Miller 1991). Therefore ongoing monitoring of nutrient budgets in this fast-growing plantation is necessary. While a standard fertiliser applied in amounts equivalent to 17, 15 and 8 kg ha^{-1} of N, P, K, respectively, at planting appears to be adequate to meet the early growth requirement of both eucalypt and acacia plantations in this study this may not always be the case. In northern Vietnam where much of the forest land is located on steep slopes (15 – 40°), the plantation soils are dominated by acidic and leached acrisols of low to medium fertility (Hung et al. 2017, Phuong et al. 2012, Sang et al. 2013) and plantation soils are characteristically very low in soil P (Dong et al. 2014, Huong et al. 2015, Sam and Binh 2001). The effect of high level of P fertiliser at planting in our study on a steep slope may have been masked by the high P leaching associated with heavy rainfall and high P-fixing capacity of tropical soils (Nambiar and Brown 1997). P deficiency could be a concern especially in successive rotations of acacia (Hardiyanto and Nambiar 2014, Huong et al. 2015) and eucalypts (Chapter 5) (see also in Gonçalves et al. (2007)).

6.1.5. Pest damages and diseases associated with silvicultural treatments in short-rotation of eucalypt and acacia plantations

There is growing concern about the impact of pests and diseases on the productivity of eucalypts and acacias plantations (Crous et al. 2017, Wingfield et al. 2015). Among the most serious biotic damaging agents of eucalypts in South East (S-E) Asia are a gall wasp *Leptocybe invasa*, a bacterial wilt pathogen *Ralstonia solanacearum* and the fungal leaf and stem blight pathogens *Calonectria quinqueseptata* and *Cryptosporiopsis eucalypti* (Dell et al. 2012, Thu 2016). Growth rates of *Acacia mangium* have been reduced from 22 − 25 to less than 15 m^3 ha^{-1} yr^{-1} as a result of fungal diseases (*Ganoderma* and *Ceratocystis*) in Sumatra, Indonesia (Harwood and Nambiar 2014). In Vietnam, Indonesia and Malaysia, *Ceratocystis* is considered an extreme threat; tree mortality rates can be up to 20% in some acacia plantations in Vietnam (Thu et al. 2012). Tropical acacias and eucalypts are also affected by termites (Calderon and Constantino 2007, Ngoc et al. 2011), with up to 30% of seedlings being infested in many young acacia and eucalypt plantations across Vietnam (Ngoc et al. 2011). However, there have been limited studies that link the management of plantation health in tropical eucalypts and acacia to silvicultural practices. In this study, even in the absence of severe insect pest and pathogen damage, it is clear how different silvicultural treatments directly or indirectly influenced tree health e.g. residue retention increased damage by termites. Pest and disease damage is very unpredictable (Bebber et al. 2014, Wingfield et al. 2015) and can be affected by a wide range of biotic and abiotic environmental conditions (Dell et al. 2012, Pinkard et al. 2010). There needs to be greater awareness of the impacts of various silvicultural regimes on plantation health and routine risk analyses for biotic damage associated with different regimes should be undertaken.

6.2. Management recommendations for steeply sloping landscapes in Vietnam

In Vietnam, plantation forests have been extensively extended since 1990s following launching of the Government Programs including "Greening the barren lands and denuded hills" (327 Program) and the "5 million hectare reforestation program" (5MHRP) (Tuan et al. 2004). By 2013, approximately 3.4 Mha of mainly acacia and eucalypt plantations had been established (MARD 2014). Managed on a rotation length of 5 – 8 years for both pulp and timber production (Nambiar et al. 2015), most of the resource is currently in the second and third rotation. There are significant challenges for sustaining the productivity of these plantations in successive rotations. The key factors that compromise sustainability have been identified as (1) management by diverse owners with varying access to capital, technology, skills and markets (Harwood et al. 2017, Nambiar et al. 2015); (2) growing trees in a wide range of terrain, soils and weather conditions; and (3) site degradation through poor management practices such as burning harvest residues and litter for land preparation and clear-cutting large areas on steep slopes (Dong et al. 2014, Dung et al. 2012, Huong et al. 2015, Nambiar et al. 2015). Sustaining the productivity of these plantations will rely on maintaining and, if possible, increasing the nutrient capital of the current forestry land base (Harwood and Nambiar 2014, Nambiar et al. 2015). The findings from this thesis will contribute to fulfil the gaps in knowledge and establish strategy to further develop guidelines in sustainable residue management and fertiliser application for industry.The following recommendations for management practices are based on findings of this thesis with current best practice and information.

6.2.1. Inter-rotational management practices for short-rotation commercial plantations on steep slopes

Harvesting:

Plantation forests in Vietnam are managed by diverse owners including small growers, public and private companies. Depending on the capacity of the owner and site conditions, harvesting operations may be conducted by manual labour with simple tools or is fully mechanical or is a combination of mechanical and manual. Mechanical harvesting has been found to increase the level of disturbance and damage imposed on soil (Nambiar and Harwood 2014). Hence, manual harvesting is recommended for plantations on steeply sloping sites.

Harvesting bark with commercial logs or stripping bark off site is a common practice in Vietnam. The findings from this thesis and other studies indicate that bark removal can significantly increase the quantities of nutrients exported from the site. Hence, retention of bark and even distribution across the site is recommended.

Site preparation for the next rotation of plantation:

Site preparation in Vietnam generally involves the burning of post-harvest residues including harvest residues, litter and understorey for easy site access, control of weeds and fire. However, burning is associated with the loss of nutrients via volatilisation, leaching, surface runoff and erosion. Burning may also be associated with the reduction in tree vigour including crown health and tree form (Chapter 4). Hence, burning needs to be avoided, especially on steep slopes. In the case that burning cannot be avoided, carrying out burning in the dry season may reduce the quantities of nutrient loss by leaching and water erosion.

Alternatively, retention of post-harvest residues and its even distribution across the site acts to conserve nutrients (Chapter 3), increase infiltration (Khan et al. 2016, Ruan et al. 2001, Ward Philip et al. 2015) and reduce water runoff and erosion (Costantini and Lcoh 2002, Edeso et al. 1999, Oyarzun and Pena 1995); hence it can be an optimal option for sustaining soil fertility and the productivity of plantations planted on steep slopes. Nevertheless, residue retention may be associated with the increased termite damage and promotion of weed development (Chapter 4). Fast development of weed during re-establishment period may increase vegetation coverage that helps to prevent surface runoff and erosion on steep slope but needs careful management to avoid competition. Post-harvest residue retention with sufficient termite control and weed management is recommended. In order to control termite, termiticides may be used to mix with soil in the nursery stage or at planting hole when planting the trees. In contrast, manual weed control is highly recommended as chemical herbicides has been listed as one of operational practices which again the forest sustainable management standard in Vietnam.

Fertiliser application:

Eucalypt and acacia plantations generally require large amount of nutrients during stand development stages (Hardiyanto and Nambiar 2014, Laclau et al. 2003) and the demand has been found decrease with stand age (Melo et al. 2016, Mendham et al. 2017). Most growth responses of plantations forest to fertiliser were observed prior to canopy closure (Forrester et al. 2010, Gonçalves et al. 2004). Hence, fertiliser application at planting and/or soon after planting is recommended.

Based on the findings from this thesis and other relevant studies, applying 200 g per tree of mixed NPK fertiliser (equivalent to 17, 15 and 8 kg ha^{-1} of N, P, K, respectively) at planting is adequate to meet the early growth requirement of both eucalypt and acacia plantations. However in Vietnam, plantation soils have a high P fixing capacity and are characteristically low in available P, especially over successive rotations. Hence, in both acacia and eucalypt plantations, larger amounts of P in the next rotation may be necessary for sustaining productivity. In addition, the P fertiliser should be applied at the base of the planting hole at planting or spot placement about 10 cm from the seedling within a month following planting to avoid the loss of P due to high P-fixing capacity of the soils, leaching, surface runoff and water erosion associated with heavy rainfall and steep slope (Gonçalves et al. 2004).

6.2.2. Recommendations for future research

- The experiment established in our study should be monitored until the end of rotation to understand the impact of burning or residue-retention treatment on soil properties and the productivity of short-rotation plantations. Since yield and site fertility appears to be declining over multiple rotations of short-rotation plantations in Vietnam especially on steep slopes, the continuation of this unique study over succeeding rotations would provide a good basis for exploring the drivers of declining productivity.
- Future research on steep slopes should pay more attention to explaining slope effects on soil properties and productivity as well as correlations of growth with factors such as surface runoff and soil erosion. For assessment of slope effects, it is recommended that the future research should apply transect sample data analysis.

- Whether additional of fertiliser, especially N and/or P, can promote the decomposition process and increase the rates of nutrient release from post-harvest residues needs investigation.
- More research into potential nutrient deficiencies in eucalypt and acacia plantations in relation to the production cycle i.e. nutrients released by harvest residues and the soil pool, especially on sloping sites, would provide an improved basis for using fertiliser cost effectively.
- The effect of silvicultural treatments to be trialled on potential biotic damage should be taken into account in any experimental design.

6.3. Conclusions

Overall, the thesis has contributed to understanding the effect of inter-rotational practices on soil properties and productivity of short-rotation plantations, especially those planted on steep slopes. The low quantity of harvest residues and relatively high fertility of the experimental site may have compromised the responses of productivity and soil properties to the silvicultural treatments applied in this study. However, subsequent amounts of nutrient released from decomposing harvest residues, even the relatively low amount of residue in this research, can supply a substantial amount of nutrients required for the growing trees. In addition, retention of post-harvest residues protects the soil from runoff and erosion. Harvest residue retention with adequate termite control and weed management is recommended for sustaining site fertility and productivity of eucalypt and acacia plantations on steep slopes. The variation in standing volume, crown health and soil properties between slope positions suggest that there is a need for further research to better understand the role of residue retention on soil erosion, biotic damage and plantation productivity on steeply sloping sites.

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